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Sixteen-Year Monitoring of Particulate Matter Exposure in the Parisian Subway: Data Inventory and Compilation in a Database

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Abstract: The regularly reported associations between particulate matter (PM) exposure, and morbidity and mortality due to respiratory, cardiovascular, cancer, and metabolic diseases have led to the reduction in recommended outdoor PM_{10} and $PM_{2.5}$ exposure limits. However, indoor PM_{10} and $PM_{2.5}$ concentrations in subway systems in many cities are often higher than outdoor concentrations. The effects of these exposures on subway workers and passengers are not well known, mainly because of the challenges in exposure assessment and the lack of longitudinal studies combining comprehensive exposure and health surveillance. To fulfill this gap, we made an inventory of the PM measurement campaigns conducted in the Parisian subway since 2004. We identified 5856 $PM_{2.5}$ and 18,148 PM_{10} results from both personal and stationary air sample measurements that we centralized in a database along with contextual information of each measurement. This database has extensive coverage of the subway network and will enable descriptive and analytical studies of indoor PM exposure in the Parisian subway and its potential effects on human health.

Keywords: particles; occupational exposure; mass concentration; environmental exposure; personal measurement; subway users' exposure

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1. Introduction

Particulate matter (PM) refers to particles, either solid or liquid, suspended in the air with sizes ranging from 2.5 to 100 µm. The span of the diameter for $PM_{2.5}$ is less than or equal to 2.5 µm while that of PM_{10} is less than or equal to 10 µm. Within electric subways, particulate matter is produced by three primary sources through the process of abrasion between the wheel-rail, wheel-brake, and the rolling stock with the power supply system [1]. Numerous studies revealed that PM mass concentrations in subways are often higher than outdoor PM concentrations. This has been observed in the subways of London [2,3], Rome [4], Lisbon [5], Shanghai [6], Seoul [7], and Paris [8]. Studies of subway PM concentrations allowed identifying several concentration determinants, including ventilation rate [9], railway rolling stock [10], presence of platform screen doors [11], railway depth [12], station passenger traffic [10], local ambient air [13], train frequency [14], and others. It was also reported that subway PMs have different physical and chemical properties compared to outdoor PMs, due to their particular shape [15], size [2], and elemental content rich in heavy metals, particularly iron [16].

It has been well established that PM exposure is associated with an increase in the incidence of inflammatory chronic diseases such as respiratory diseases [17,18], cardiovascular diseases [19,20], cancer [21], metabolic diseases such as diabetes [22], and also with mortality [23]. The metallic components of PM appear to play an important role in oxidative stress induction and the resulting inflammatory process. Oxidative stress and inflammation are considered the key elements in the pathogenesis of several chronic diseases, particularly those related to PM exposure [24,25]. PM size also plays an important role in pathogenesis, since fine particles, such as $PM_{2.5}$ and ultrafine particles (UFPs, i.e., particles with an average aerodynamic diameter smaller than 0.1 μm) are more likely to reach distal airways and lung alveoli and translocate into the bloodstream [26–28]. The greater adverse health effects of UFPs compared to those of PMs that have been demonstrated in different studies [29] might also be explained in part by the large surface area (at the same volume) in contact with pulmonary alveoli [26,30]. Given the evidence of the adverse health effects of PM exposure [31,32], the World Health Organization (WHO) revised its recommended air quality guidelines (AQG) in 2021 and reduced the AQC levels for both $PM_{2.5}$ and PM_{10}. Today, the WHO recommended annual mean AQG level for PM_{10} and $PM_{2.5}$ is set to 15 $\mu g/m^3$ and 5 $\mu g/m^3$ while the recommended daily mean (24 h) is set to 45 $\mu g/m^3$ and 15 $\mu g/m^3$, respectively [33]. It is worth mentioning that in its assessment, the WHO considered the exposure through ambient air, which encompasses the exposure in both outdoor and indoor environments. Therefore, the application of the WHO's AQGs, which have been established for ambient PM, cannot be directly relevant for subway PM exposure.

Despite the accumulating knowledge on the adverse health effects of ambient PM, studies on subway PM exposure remain rare [34–38]. Moreover, none of the existing studies have considered long-term exposure (i.e., longer than two weeks), to enable prospective or retrospective exposure assessment, which is necessary in epidemiology. This situation precludes any conclusion regarding the long-term effects of occupational exposure to PM on subway workers' health [39].

In France, occupational exposure to chemicals is regulated by the French labor law. In this regulation, insoluble or poorly soluble particles in the size range of PM are considered as dusts without specific effect (i.e., dusts that do not present any effect other than those resulting from the consequences of pulmonary overload, in the absence of having been able to demonstrate a specific effect) [40]. For these dusts, two occupational exposure limits (OELs) will take effect on 1 January 2023. The OEL for the alveolar deposition fraction of dusts, assessed over an eight-hour period, is set at 0.9 mg/m^3, and that of total deposition fraction or total dusts is set at 4 mg/m^3 for (article R-4222-10 of the French labor law). However, the obligation to monitor occupational exposure to PM only applies to settings where specific pollution is generated. As such, in the Parisian subway network (14 metro lines and two intercity lines, all powered by electricity), the regulation applies differently across various jobs. For the three jobs that constitute the majority of the underground workforce of 15,000 individuals (i.e., locomotive operators, security guards, and station agents), there is no regulation in place toward occupational exposure. Despite this, several exposure measurement campaigns including PM measurement have been conducted. The first, very exploratory, measurements started in the late 1990s. However, a more systematic methodology was established and implemented in 2004, subsequent to a research project on subway air quality.

Our objective was to conduct an inventory of the historical PM measurements conducted in the Parisian subway network since 2004, and to create a database of measured $PM_{2.5}$ and PM_{10} concentrations along with contextual information of each measurement.

2. Materials and Methods

2.1. PM Measurements Conducted in the Parisian Subway

PM measurements have been usually conducted within the company in two ways: stationary (using fixed samplers) or personal (using portable samplers positioned within proximity to the worker). The department housing the air quality section is solely responsible for the monitoring of stationary PM concentrations. In contrast, personal measurements are usually commanded either by the department housing the occupational health section (at the mandate of occupational physicians) or by departments specific to each profession. Departments have the flexibility in commanding measurement campaigns either by mandating the company-affiliated laboratory specialized in physicochemical measurement, or by mandating other laboratories external to the company, certified for physicochemical measurements.

2.2. Identification of Available PM Measurement Data

We contacted all the departments susceptible to have commanded PM measurements and scheduled two meetings in order to identify all existing PM measurement campaigns and their data. The first meeting aimed to formally inform them about the study and to set the data identification and collection procedure. This meeting was held in the presence of two occupational physicians from the health service, hygienists from all departments, as well as with officials of the company-affiliated laboratory. The second meeting was held individually with each department in the presence of the department head and hygienists and aimed to review all exposure measurement campaigns conducted by external laboratories and to identify those where PM concentrations have been measured.

The company-affiliated laboratory provided the identified data either through an online company data repository or in paper format (i.e., for the reports prior to 2008). In fact, PM measurement results were recorded in the campaign reports, which were cataloged and kept for a minimum of ten years.

After identifying and reviewing all available reports of PM measurement campaigns conducted in the subway network, we excluded those conducted due to exceptional requests, such as the observation of a dust cloud, or measurements other than $PM_{2.5}$ and PM_{10}. All other reports were used for quantitative and contextual data extraction.

2.3. Analytical Methods Considered

The PM mass concentration measurements at the Parisian subway network were conducted using three different methods and devices (Figure 1).

Figure 1. Devices used in PM measurement campaigns conducted within the Parisian underground subway: Left: Gravimetric method equipment [41]; Middle: TEOM (model: 1400; brand: Thermo Scientific); Right: DustTrack (model: DRX; brand: TSI).

The gravimetric method represents the reference method on which PM regulations in both the United States (US) and the European Union (EU) are based [42,43]. Its working principle consists of weighting PM left on the sampler's filter. The samplers' pump collects PM by sucking air through a pre-weighed Teflon filter (pump flow rate: 4 L/min) that is re-weighted under controlled conditions to determine the quantity of PM accumulated on it. The PM mass concentration is then estimated using sample volume measurements, and converted into occupational exposure based on an 8 h shift, i.e., the 8-h time-weighted average (TWA) exposure [44].

The DustTrack is a real-time optical device that operates by light scattering using a laser diode. The generated signal is converted into a voltage that is proportionate to the PM mass concentration of the sample [45]. This device (model: DRX, brand: TSI), used to conduct the measurements, was intended for hierarchical comparison of recorded PM concentrations between stations and, on a larger scale, between subway lines.

The *Tapered* Element *Oscillating* Microbalance (TEOM) is another direct-reading instrument widely used at the company. In this device (model: 1400; brand: Thermo Scientific), PM of a specific size range is pumped through a tube, and the difference in magnitude detected on the filter's frequency induced by the collection of particles is translated into particle mass [46]. This device is validated by the French accreditation committee (COFRAC) and provides average concentrations over a period of 15 min for $PM_{2.5}$ and PM_{10}.

2.4. Construction of a PM Database

The relevant contextual measurement data, as well as the measured PM concentration values were extracted from the reports using an ad hoc developed data extraction form to feed a database, that is structured in a similar way to the ExpoSYN [47]. The ExpoSYN database contains quantitative data on occupational exposure to five major lung carcinogens and has been used to develop a job-exposure matrix SYN-JEM [48] enabling retrospective quantitative exposure in epidemiological studies. Table 1 describes the content of our database and the data format. Besides numeric values of PM concentrations, about 30 contextual variables characterizing each recorded PM measurement were documented. These data will later be used in a statistical analysis of subway PM exposure and its determinants [49].

Table 1. Variables included in the Subway-PM database.

Type of Informations	Variables	Label	Format
General	Report_ID	Report of measurement campaign	Alphanumeric
	Report_Date	Date of final report	DD-MM-YYYY
	Commander	Department ordering measurements	Text
	Executor	Laboratory executing samplings and analyses	Text
	Worker_ID	Reference characterizing the worker	Text
	Sample_ID	Reference characterizing the sample	Text
	Subway_line	Train line	Number
	Subway_station	Train station	Text
	Rolling_stock	Rolling stock type operating on the train line	Alphanumeric
	Subway_frequency	Train frequency	Number
	Fans_number	Number of operating fans in the train station	Number
	Subway_setting	Underground or Above ground or Hybrid	Text
Job_characteristics	Job	Station agent or Security guard or Locomotive operators	Text
	SA_sector	Station agent's assigned workplace sector	Text
	SG_Sector	Security guard's assigned workplace sector	Number
	LEV	Presence of local exhaust ventilation at workplace	Yes/No
Measurement	Sample_date	Date of the measurement	DD-MM-YYYY
	Weekday	Day of the week	Text
	Sample_duration	Duration of samplings	Number
	Sample_dur_unit	Min or Hour or Day	Text
	Sampler_Place	Sampler location at the station	Text
	Sampler_Height	Height in meters	Number
	Sample_type	Personal or Stationary	Text
	Starting_Time	Starting time of measurement	HH-MM
	Meas_conc	Measured concentration value	Number
	Meas_unit	Measured concentration unit	Text
	TWA_Conc	Time-weighted average concentrations	Number
	TWA_unit	Adjusted TWA unit	Text
	Hours_TWA	Time duration TWA in hours	Number
	Analyse_method	TEOM or Dustrak or Gravimetric method	Text
	LOQ_value	Limit of Quantification value	Text
	LOQ_cat	Above the LOQ or Bellow LOQ or Equal	Number
	LOQ_unit	Unit of LOQ	Text

Within this database, mass concentrations were distinguished between the analytical methods and also, between raw measured values and 8 h TWA values, which were assessed using the gravimetric method. The jobs and workplace locations were also systematically extracted.

2.4.1. Definition of Jobs

Jobs were defined according to the worker's occupation, workplace location, and tasks performed. There are three main occupations in the underground subway network (i.e., locomotive operators, security guards, and station agents). Among station agents, we distinguished those with a fixed workplace (at the ticket counter desk at a subway station) and mobile station agents. Moreover, station agents are assigned within each line to a geographic sector (i.e., East, West, North, and South) covering a certain portion of stations. The security service of the company, employing security guards, is divided into five geographical zones (GZ). The city of Paris is covered by the GZ1, while the other four zones cover the suburbs of Paris. Since the work-assignment logic is different for each job, two additional variables were created to specify the station agents' sector and the security guard's geographical zone. All locomotive operators are assigned to a specific subway line with the exception of a small number of reserve locomotive operators who can operate on several lines.

2.4.2. Missing Data

The missing data were classified into three modalities: 1. "no relevance" (i.e., data not documented), for example, for a job variable in case of stationary measurements; 2. "no measurement" (i.e., data not measured), for example, in case of renovation work at the station; and 3. "no data" (i.e., data absent despite its measurement, for example, in case of the non-respect of the analytical protocol or due to a dysfunction of the measuring instrument.

2.5. Statistical Analysis

Statistical analysis consisted of descriptive estimates of the PM concentrations stratified by type of measurement campaign and by type of measurement method. Analysis was conducted separately for $PM_{2.5}$ and PM_{10}. Whenever possible we estimated monthly and annual average concentrations by aggregating data from the same measurement method. Furthermore, to explore the usefulness of this database for monitoring temporal and spatial variation in PM concentrations, we summarized and visualized the data using box plots. All analyses were conducted using STATA (version 16) statistical software.

3. Results

3.1. Stationary Measurement Campaigns

Two types of stationary measurement campaigns were identified (Table 2). The first type records measurements once in a while, and is referred to as occasional measurements throughout this article. The second type records the measurement results repeatedly, and will be referred to as continuous measurements.

Table 2. Inventory of PM measurement campaigns conducted in the Parisian subway (2004–2020).

Campaign Name	Type and Place of Air Sampling	Network Coverage	Calendar Period	Device Used (PM Size)	Measurements Time Interval	Measurement Duration	Measurement Shift	Reported PM Concentration	Number of Recorded Measurements N (%)	
									$PM_{2.5}$	PM_{10}
Squales	Stationary (1 platform)	6 stations (l.1; l.4; l.9; 3 on RER A)	January 2004–November 2020	TEOM (PM 10 with or without PM 2.5)	15 min	24 h/7 days	Continuous	Daily	2531 (43.2%)	10,510 (57.9%)
								Monthly	117 (2.0%)	369 (2.0%)
						5:30–13:30		Daily	2531 (43.2%)	6596 (36.3%)
								Monthly	– (0%)	– (0%)
Mapping-2014	Stationary (2 platforms)	l.1 and l.9 stations	January 2014	DustTrak (PM 2.5; PM 10)	30 s	15 min	7:00 to 9:00	Average concentration on 30 min	122 (2.1%)	122 (0.7%)
Mapping-2016	Stationary (1 platform)	All network lines and stations	June–December 2016	DustTrak (PM 2.5; PM 10)	30 s	30 min	7:30 to 9:30	Average concentration on 30 min (1 platform)	441 (7.5%)	441 (2.4%)
Occupational exposure assessment 2016	Personal (3 locomotive operators per line)	along all network lines	November–December 2016	Gravimetric method * (PM 2.5; PM 10)	–	7 h workshift	Morning (≃5:00 to 12:00)	exposure (8 h TWA)	47 (0.8%)	45 (0.2%)
	Personal (1 locomotive operator per line)			DustTrak (PM 2.5; PM 10)	30 s	≃ 4 h		Average concentration on ≃4 h	14 (0.2%)	14 (0.1%)
Occupational exposure assessment 2017	Personal (each GZ team)	GZ 1, 2, 3 †	January–February 2017, February 2018	Gravimetric method * (PM 2.5; PM 10)	–	7 h work shifts	Afternoon (≃12:00 to 19:00)	Exposure (8 h TWA)	8 (0.1%)	8 (4‰)
				DustTrak (PM 2.5; PM 10)	30 s	≃ 4 h		Average concentration on ≃4 h	9 (0.2%)	9 (5‰)
ROBoCoP pilot study 2019	Personal (for each station agents type)	2 stations of l.7 (station agents)	October 2019	Gravimetric method * (PM 2.5; PM 10)	–	10 days work shifts	Afternoon (≃12:00 to 19:00)	exposure (8 h TWA)	20 (0.3%)	20 (0.1%)
	Personal	Along l.7 (locomotive operators)	October 2019	Gravimetric method * (PM 2.5; PM 10)	–	9 days work shifts	Morning (≃5:00 to 12:00)	Exposure (8 h TWA)	8 (0.1%)	8 (4‰)
	Personal	GZ 1 (security guards)	November 2019	Gravimetric method * (PM 2.5; PM 10)	–	9 days work shifts	Afternoon (≃12:00 to 19:00)	Exposure (8 h TWA)	8 (0.1%)	8 (4‰)

*: Teflon filter and pump debit (4 L/min); †: GZ 1: Paris; GZ 2: La Défense; GZ 3: Bobigny.

In terms of occasional measurements, two campaigns were conducted in order to map PM concentrations over the subway network. The measurements were conducted on train platforms using the DustTrak device, and average concentrations were estimated based on the measurement duration. The first of the two occasional mapping campaigns of stationary PM measurements was conducted in 2014 (January) on lines 1 and 9. The measurements lasted for 15 min on platforms in both directions between 7:00 a.m. and 9:00 a.m. (i.e., 30 min per station). The second campaign of stationary PM measurements was conducted in 2016 (between June and December) on all stations of the subway, comprising 14 subway lines and two intercity lines, namely, RER A and RER B. The RER lines (regional express network, from *Réseau Express Regional* (RER) in French) operate less frequently but are faster and cover regions outside the city, compared to regular subway lines. The measurements lasted for 30 min on platforms in a single direction between 7:30 a.m. and 9:30 a.m. Exceptionally, when platforms were not facing one another, measurements were taken for both directions. It should be noted that measurements were not conducted at uncovered aerial stations that constitute (over the total number of stations) a proportion equal to or less than 10% on all lines. The only exceptions are line 2 and line RER B, which have 16% and 84% of uncovered aerial stations, respectively. DustTrack measurements are carefully controlled through systematic calibration to zero, before each usage, of the device in a particle-free environment (environment supplied with the device). Moreover, the company-affiliated laboratory in charge of PM measurements manages to annually send each DustTrack device to a metrology laboratory to ensure the full calibration. Data measurements are also controlled through the validation of an expert physical–chemical engineer at the laboratory. Each significant change in concentration must be interpreted with regard to the context of the measurements. In the absence of explaining factors, these data are considered aberrant and invalid. Nevertheless, this is seldom the case, and we have no invalidated measurements in the database.

In terms of continuous measurements, in 1997, the company decided to set up an underground air quality monitoring program, named "Squales". This program aimed to monitor trends at two subway stations "Chatelet" on line 4 and "Franklin Roosevelt" on line 1 and at three intercity train stations on the RER A line: "Chatelet les Halles", "Auber", and "Nation" of the same direction, namely, Boissy-Saint-Leger (Figure 2). Measurements within this monitoring program have also been conducted on other stations but discontinuously (over several months or years, Table 2). Squales measurements were conducted using TEOM devices (Figures 1 and 2), such devices are certified by the French accreditation committee (COFRAC); they must be calibrated on a regular basis to comply with the standards. Since 2004, the measurement results were provided in monthly reports by the company-affiliated laboratory, although in varying levels of detail. Some reports contained daily average concentrations over 24 h, as well as monthly average concentrations, while others only included monthly average concentrations. PM_{10} concentrations were measured at all stations, as opposed to $PM_{2.5}$ concentrations, which were taken at five among the nine stations that were subjected to measurements within the Squales monitoring program. Incidentally, within the stations that record $PM_{2.5}$ concentrations, measurements are discontinuous for certain periods. Additional measurements obtained during the operational hours of the subway (i.e., between 5:30 a.m. and 1:30 a.m.) for both $PM_{2.5}$ and PM_{10} were included in the reports during certain periods. Furthermore, Squales measurements do lack data for certain months/years in some stations for different reasons but mostly due to periods of renovation when measurements have ceased.

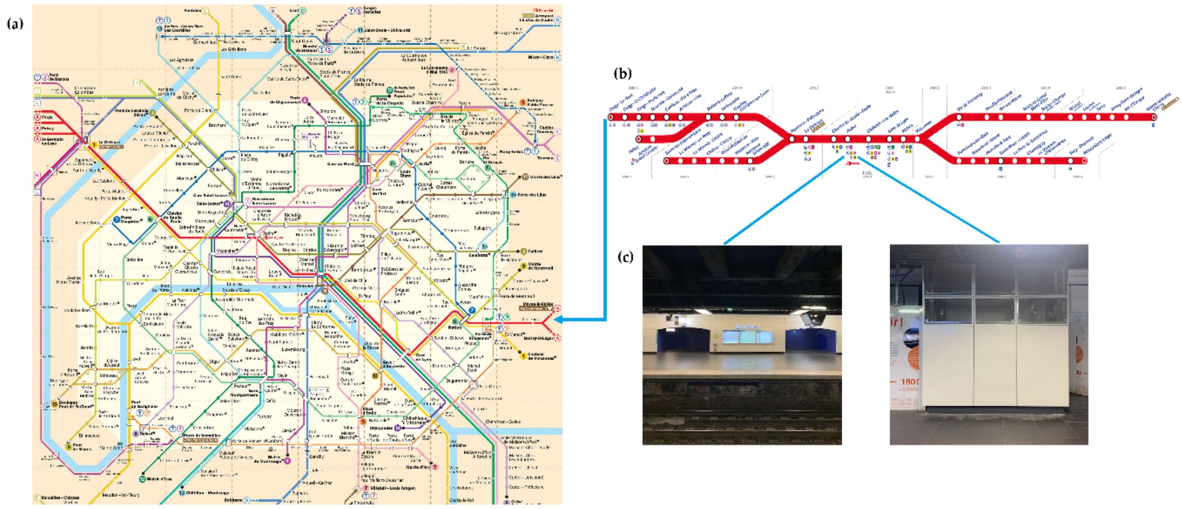

Figure 2. One station on the intercity line RER A of the Parisian subway network chosen to illustrate the PM monitoring measurements: (**a**) Map of the Parisian subway network. (**b**) Map of the *RER A* intercity line. (**c**) Cabinet dedicated for PM measurements (right figure) on the Auber station platform (left figure).

3.2. Personal Measurement Campaigns

Three personal measurement campaigns have been identified (Table 2). All estimated an 8-h time-weighted average (TWA) exposure using the gravimetric method. The campaign conducted in 2016 was focused on locomotive operators. The 2017 campaign was focused on security guards, while in 2019, three types of subway jobs were monitored: locomotive operators, security guards, and station agents.

In the campaign conducted in 2016, measurements were conducted on a single day for each subway and intercity line for locomotive operators on active duty during their morning shift (from November to December). In addition, three locomotive operators were monitored using the gravimetric method, while one of them was monitored by the DustTrak at the same time. The DustTrak measurements were taken at the start of the shift, but they were shorter due to the device's reliance on battery life, which only lasts around four hours.

In the 2017 campaign, measurements were conducted during a three-day period on one security guard team for each of the three geographic zones (GZ1-Paris, GZ 2-La Defense, and GZ 3-Bobigny), while on active duty during their afternoon shift (in January and February). Every security team was monitored by the gravimetric method and the DustTrak on a daily basis. The gravimetric measurements were recorded over the work shift, while the DustTrak measurements were shorter.

In the campaign conducted in October and November 2019, which corresponds to a pilot study conducted as part of a research project ROBoCoP, measurements were only conducted using the gravimetric method every day for two weeks of active duty for each of the three jobs (i.e., station agents, locomotive operators, and security guards [50,51]. Two measurements were conducted on station agents during their afternoon shift on subway line 7 at two distinct stations: one at the information desk with two fixed station agents and another one on a mobile station agent. One series of measurements operated every day in turn on one of the three locomotive operators during their morning shift. Finally, the third series of measurements operated every day on a security team from the Paris GZ, during their afternoon shift.

3.3. Database Measurements Content

In total, 372 measurement campaign reports were identified and checked for eligibility by the work group. Five reports were excluded. A total of 18,148 PM_{10} and 5856 $PM_{2.5}$ measurements recorded between January 2004 and November 2020 were compiled in the database. For PM_{10} measurements: the Squales-monitoring program accounted for 96.3% (N = 17,475 including 17,106 records of daily average concentrations and 369 records of monthly average concentrations) of the recorded measurements (24 h or during the operational hours of the subway, i.e., 5:30 a.m.–1:30 a.m.); occasional mapping campaigns for 3.1% (N = 563). Personal measurement campaigns accounted for only 0.6% (N = 112). For $PM_{2.5}$, these proportions were 88.4% (N = 5179 including 5062 records of daily average concentrations and 117 records of monthly average concentrations), 9.6% (N = 563), and 1.9% (N = 114), respectively (Table 2). Among the missing data in PM_{10} measurement records, the number of "no data" accounted for 5.7% (N = 866) in the Squales-monitoring program and 6.2% (N = 9) in personal measurement campaigns, while there were no missing data in the occasional mapping campaigns. For $PM_{2.5}$ measurements, these proportions were 6.9% (N = 382) in the Squales-monitoring program and 4.9% (N = 7) in personal measurement campaigns, while there were no missing data in the occasional mapping campaigns.

Figure 3 presents the annual distributions of PM_{10} and $PM_{2.5}$ concentrations measured on the Auber platform of the RER A intercity line (direction: Boissy Saint Leger) from 2010 to 2018 within the Squales-monitoring program (using TEOM). For both types of PM, we observed a large variation in monthly average concentration in 2010, 2013, and 2015. While annual average concentration did not change much between 2010 and 2018 (PM_{10} concentrations decreased from 170 to 130 $\mu g/m^3$, while $PM_{2.5}$ concentrations decreased from around 70 to 55 $\mu g/m^3$), there was a marked decrease in PM exposure between 2013 and 2017 in both $PM_{2.5}$ and PM_{10}. For both particle sizes, this corresponds to a reduction of approximately 25%. The drop in PM concentration initiated in 2014 coincides with the change in rolling stock, with MS61 (suburban equipment built in 1961) being replaced by MI09 (Intercity equipment bought in 2009).

Despite some fluctuations, the PM_{10} concentrations recorded at different stations of the Squales network (three stations belonging to the RERA line: Nation, Auber, and Chatelet les Halles noted as "ChateletLH" on the graph; and two other stations Franklin Roosevelt and Chatelet belonging to line 1 and 4, respectively) show a general decrease since 2017 (Figure 4). It is worth noting that the decreasing slope was of the same order of magnitude for the four stations concerned by this between 2017 and 2020. The only exception is the Auber station, for which we only had data from 2016 to 2018.

To illustrate the spatial distribution of PM concentrations over the network, we used the measurements recorded by DustTrack, and presented the average concentrations. In Figure 5, we presented the distributions of $PM_{2.5}$ and PM_{10} concentrations recorded in the 2016 mapping campaign at three subway lines (line 1; line 2; and line 6). We chose these three lines as they cover different geographical areas and serve emblematic monuments within the French capital. On the one hand, we observe a proportionality of $PM_{2.5}$ and PM_{10} concentrations between the three lines that were the subject of the graphical representation (line 1; line 2; and line 6). The median of the concentrations of line 1 is slightly higher than that of line 2, which is itself much higher than that of line 6. On the other hand, we can observe that the intra-line distribution of $PM_{2.5}$ and PM_{10} (represented by the width of the box) is similar for each of the three lines mentioned. The levels of these $PM_{2.5}$ and PM_{10} concentrations present more heterogeneity for line 2 than for line 1, while line 6 seems relatively homogeneous. The analysis of contextual information along with data on exposure determinants, such as topography, ventilation, and architecture of the different stations on the same line, will be helpful to better understand these figures and results.

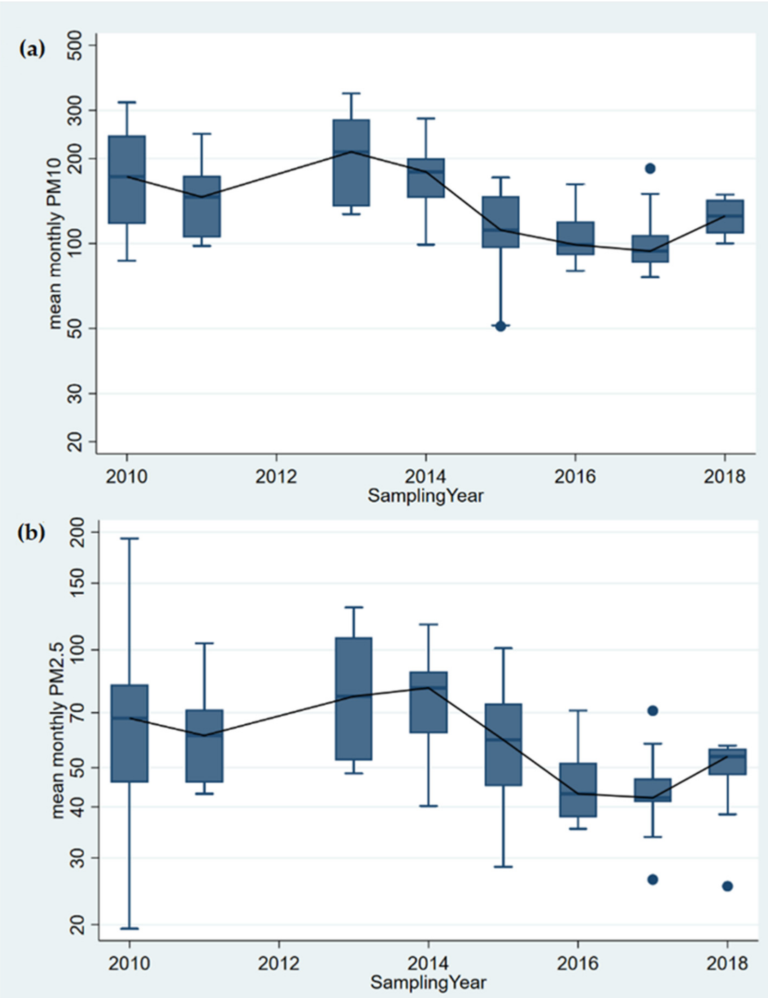

Figure 3. PM mass concentration monitored at "Auber" station of the Parisian subway network (using TEOM device): (**a**) PM_{10} mass concentration. (**b**) $PM_{2.5}$ mass concentration.

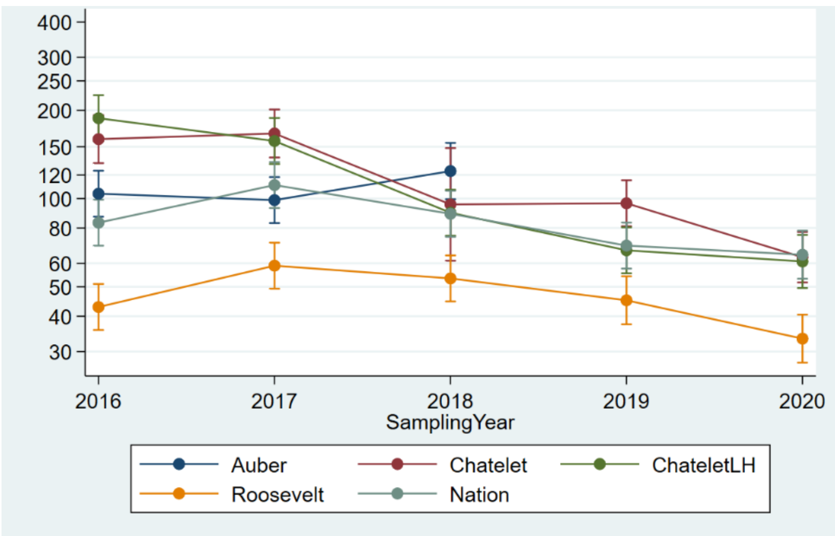

Figure 4. Geometrical means and confidence intervals of the PM_{10} mass concentration monitored on five stations of the Parisian subway network over the five last years of the data collection (using TEOM). On the *Y*-axis: Yearly average (95% CI) of monthly stationary PM_{10} measurements (μg/m^3) since 2016 according to five underground stations.

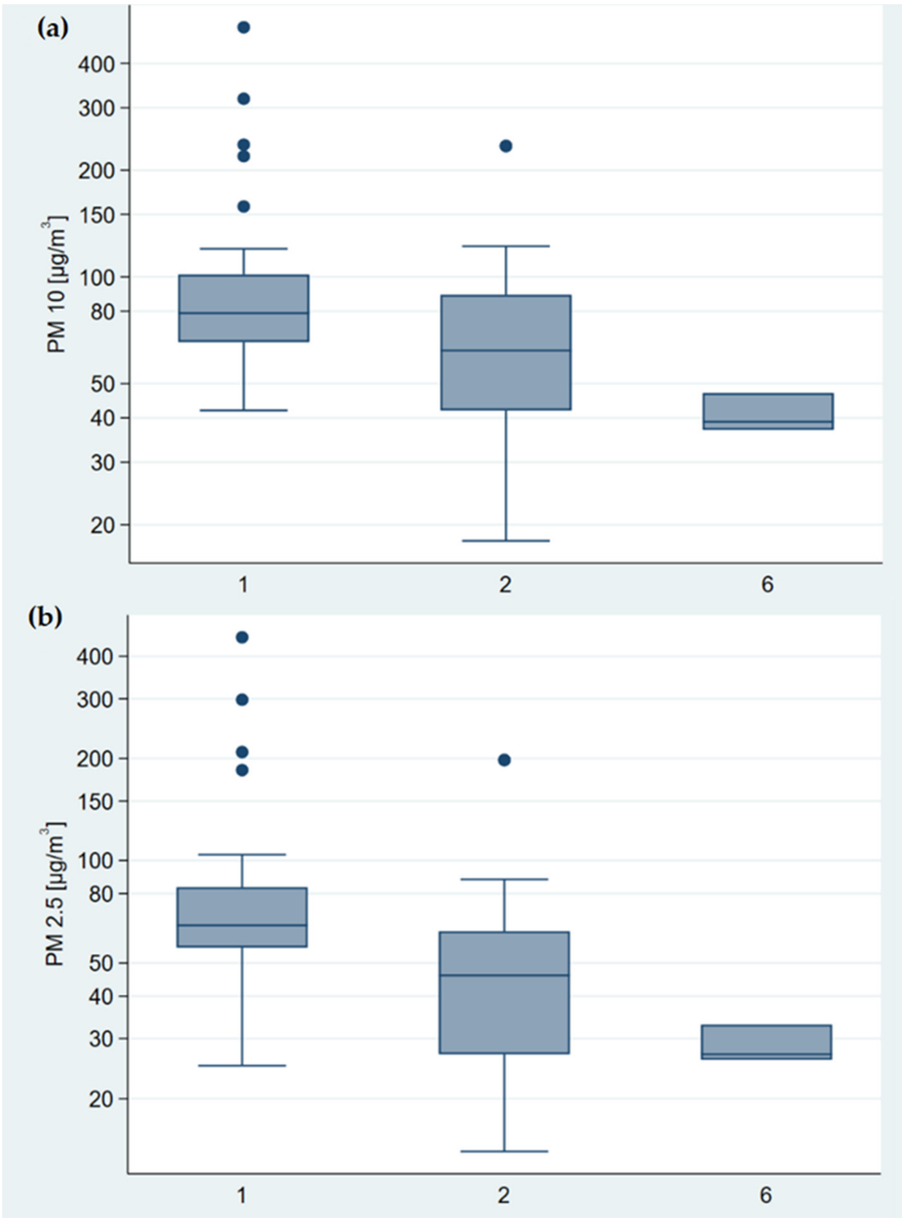

Figure 5. PM mass concentrations monitored in underground stations of three metro lines (l.1; l.2; l.6) deserving emblematic monuments within the French capital (using DustTrack device): (**a**) PM_{10} mass concentration. (**b**) $PM_{2.5}$ mass concentration.

4. Discussion

4.1. Strengths and Limitations of the Database

The constructed database is divided into three types of measurements, i.e., personal measurements, occasional mapping measurements, and continuous measurements conducted on a few stations of the Parisian subway network. Among these data, stationary measurements comprise the vast majority of results. According to Borghi et al., all types of measurements should be used to obtain the most accurate retrospective exposure assessment [52].

The personal measurements, on the downside, are rare but, on the upside, they were recorded in realistic working conditions while having the added advantage of using the standard gravimetric technique. Furthermore, the campaign conducted in 2019 on the three types of jobs was conducted over a relatively long period of two weeks, which should serve as a reflection of regular professional activity. These measurements should be used as a starting point to assess occupational exposure, as suggested in the literature [53].

The stationary mapping campaign measurements were conducted by the DustTrack device occasionally: however, on the upside, the mapping campaign maintained a high coverage of the underground subway. The measurements operationalized using devices such as the DustTrack, often lacked accuracy. Therefore, recommendations related to calibration must be followed in order to undertake comparisons of these recorded measurements with personal measurements and Squales measurement campaigns using the gravimetric technique and TEOM [54].

Finally, the stationary measurements within the Squales-monitoring program were conducted on the subway network at a few selected stations; however, these measurements were conducted over for more than a decade using the TEOM device, which is validated and certified in France. These measurements will be analyzed as a function of a certain number of potential determinants for PM concentrations and will assist in the modeling of temporal trends.

The combination of measurements and subsequently the strengths identified in each campaign will compensate for their limitations and will serve for assessing PM exposure retrospectively. In fact, by containing more than a decade of measurements, this database represents the longest documentation period for PM measurements in subway environments found in the literature.

Indeed, the combined use of different types of data will require rigorous processing of the raw data, including between-method calibration, time standardization, and application of appropriate conversion equations to render them comparable. This work should be conducted as a next step, prior to a comprehensive statistical analysis of PM exposure and its potential determinants. The absence of data prior to 2004 is the main limitation of the current study and resulting database. This limitation can hardly be managed in the future, as PM exposure monitoring in subways is still not compulsory in many countries.

Since the presence of ultrafine particles (UFPs) in subway networks was pointed out as a concern, it seems suitable in the future to include UFP concentrations in our database as well. As for the time being, UFPs are not subject to any regulation, and their measurements in the Parisian subway are still exceptional [55–57]. Moreover, details on the chemical composition of PMs, especially their heavy metal content, which plays a role in the biological inflammation caused by these pollutants [24,25], would be important to assess in the future.

4.2. Relevance of the Database for Monitoring PM Exposure and Investigating Its Origins

The elaborated database will be used to analyze PM exposure by comparing concentrations recorded in different locations within the Parisian subway network and beyond. This will provide a better understanding of the exposure levels to which both the agents working in this environment and the millions of subway passengers, who use it on a regular basis, are exposed. For example, using the data for Auber station in 2018, we clearly see that PM concentrations in the subway are much higher than outdoor concentrations in Paris and its suburbs. At Auber station, the annual average concentration was nearly 130 $\mu g/m^3$, while that recorded by the 10 outdoor air monitoring stations (near the main road axes) using the same analytical method (TEOM) ranged from 22 to 42 $\mu g/m^3$. These data suggest that the PM present in the subway has, for the most part, an internal origin. Since all these concentrations massively exceed the recently updated WHO AQGs (i.e., 5 $\mu g/m^3$ for $PM_{2.5}$ and 15 $\mu g/m^3$ for PM_{10}), monitoring and recording of this exposure for epidemiological study purposes is important

This database will also be used to carry out further analysis on PM concentrations in relation to a variety of potential determinants, similar to what was conducted on the effects of changing parameters in the subway system (e.g., the rolling stock) on $PM_{2.5}$ concentrations recorded between 2011 and 2018, in the subway of Toronto [58]. Several parameters have been identified in the literature as potential determinants of PM exposure. Among these parameters, we are currently collecting data on the depth of the rails (distance from the surface above ground), the type of railway rolling stock, the passenger frequency at the station, the number of transitory lines at the station, the presence (or absence) of platform screen doors, the number of fans operating in the station, the station design (underground; semi-underground; aerial), the train frequency, and the season. In order to identify the determinants of PM concentrations in the Parisian subway, we intend to conduct analyses on the effect of these parameters on PM concentrations using statistical modeling. This will allow us to have a better understanding of the variability of PM concentration levels across the Parisian subway network. Moreover, this could subsequently facilitate the implementation of exposure control interventions in the subway network (e.g., installation of platform screen doors) and assessment of their effectiveness.

4.3. Relevance of the Database for Retrospective Exposure Assessment

The elaborated database will enable the construction of a job–exposure matrix (JEM) for subway workers and use it in epidemiological studies. JEMs are an efficient tool widely used in occupational epidemiology in order to classify job titles based on the knowledge of exposure while this job or a particular task is performed [59]. The JEM that will be developed could become a valuable tool for retrospective exposure assessment as well as being the first JEM for PM exposure in the subway environment. As we collected a large volume of quantitative results of PM measurements within the database, the combined use of these data, after appropriate calibration, will allow the construction of a quantitative JEM. Thanks to the contextual information available in the database, this future JEM will have three dimensions: the job, the work-assignment site, and the calendar period.

Quantitative JEMs, unlike qualitative or semi-quantitative JEMs, allow the quantitative assessment of occupational exposure to be performed retrospectively. This feature is highly valuable in epidemiological studies aimed to investigate exposure–response relationships. Indeed, any inaccuracy in the exposure assessment might have a significant impact on the findings in terms of relationships between exposure and its health effects [60]. The future JEM for subway PM exposure could then be used to estimate workers' cumulative exposure based on their occupational history, which is retraced based on human resources data in the EDGAR cohort of 45,000 subway employees dating back to 1 January 1980 [61].

Consequently, our database offers a great opportunity to develop a JEM for PM exposure in the Parisian subway and use it for investigating their relationship with health impairments in the cohort of Parisian subway workers. This would expand the scientific understanding of the health effects of long-term exposure to PM in subway environments, which is presently lacking in the international literature. It should be noted that there are already several instances of quantitative JEMs on air pollutants in the literature [48,62–65], including one on $PM_{2.5}$ and total PM [63].

Further work will be included in the development of the JEM. The time interval that should define the step of the period variable constituting the JEM, based on relatively homogenous concentration levels [60], will be defined later through the time trends statistical modeling that will be applied to the Squales-monitoring program measurements. Furthermore, the JEM will be constructed concurrently with incorporating the expertise of hygienists and occupational physicians, who may contribute their knowledge from the field of PM exposure determinants [66].

5. Conclusions

We made an exhaustive inventory of the PM10 and PM2.5 measurement records available since 2004. Overall, 24,004 quantitative records of PM concentrations were centralized in a database along with contextual data on exposure measurement campaigns, which permits to inform occupational and environmental PM exposure in the Parisian subway over the last 16 years. The data show that PM concentrations have declined over the last five years. However, the current PM exposure is still higher than the WHO air quality guidelines. The database constructed in this study will be used along with contextual data to examine the exposure determinants in order to identify those that enable a reduction in PM exposure (e.g., platform screen doors and ventilation). The data will be also used for constructing a job–exposure matrix for PM in the Parisian subway, as part of a retrospective occupational exposure assessment in the frame of an epidemiological study of subway workers.

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References

1. Sitzmann, B.; Kendall, M.; Watt, J.; Williams, I. Characterisation of airborne particles in London by computer-controlled scanning electron microscopy. *Sci. Total Environ.* **1999**, *241*, 63–73. [CrossRef]
2. Seaton, A.; Cherrie, J.; Dennekamp, M.; Donaldson, K.; Hurley, J.F.; Tran, C.L. The London Underground: Dust and hazards to health. *Occup. Environ. Med.* **2005**, *62*, 355–362. [CrossRef] [PubMed]
3. Smith, J.D.; Barratt, B.M.; Fuller, G.W.; Kelly, F.J.; Loxham, M.; Nicolosi, E.; Priestman, M.; Tremper, A.H.; Green, D.C. $PM_{2.5}$ on the London Underground. *Environ. Int.* **2020**, *134*, 105188. [CrossRef]
4. Perrino, C.; Marcovecchio, F.; Tofful, L.; Canepari, S. Particulate matter concentration and chemical composition in the metro system of Rome, Italy. *Environ. Sci. Pollut. Res.* **2015**, *22*, 9204–9214. [CrossRef] [PubMed]
5. Correia, C.; Martins, V.; Cunha-Lopes, I.; Faria, T.; Diapouli, E.; Eleftheriadis, K.; Almeida, S. Particle exposure and inhaled dose while commuting in Lisbon. *Environ. Pollut.* **2019**, *257*, 113547. [CrossRef] [PubMed]
6. Mao, P.; Li, J.; Xiong, L.; Wang, R.; Wang, X.; Tan, Y.; Li, H. Characterization of Urban Subway Microenvironment Exposure—A Case of Nanjing in China. *Int. J. Environ. Res. Public Health* **2019**, *16*, 625. [CrossRef] [PubMed]
7. Kim, K.Y.; Kim, Y.S.; Roh, Y.M.; Lee, C.M.; Kim, C.N. Spatial distribution of particulate matter (PM_{10} and $PM_{2.5}$) in Seoul Metropolitan Subway stations. *J. Hazard. Mater.* **2008**, *154*, 440–443. [CrossRef]
8. Raut, J.-C.; Chazette, P.; Fortain, A. Link between aerosol optical, microphysical and chemical measurements in an underground railway station in Paris. *Atmos. Environ.* **2009**, *43*, 860–868. [CrossRef]
9. Song, X.-Y.; Lu, Q.-C.; Peng, Z.-R. Spatial Distribution of Fine Particulate Matter in Underground Passageways. *Int. J. Environ. Res. Public Health* **2018**, *15*, 1574. [CrossRef] [PubMed]
10. Tu, M.; Olofsson, U. PM levels on an underground metro platform: A study of the train, passenger flow, urban background, ventilation, and night maintenance effects. *Atmos. Environ. X* **2021**, *12*, 100134. [CrossRef]
11. Martins, V.; Moreno, T.; Minguillón, M.C.; Amato, F.; de Miguel, E.; Capdevila, M.; Querol, X. Exposure to airborne particulate matter in the subway system. *Sci. Total Environ.* **2015**, *511*, 711–722. [CrossRef] [PubMed]
12. Colombi, C.; Angius, S.; Gianelle, V.; Lazzarini, M. Particulate matter concentrations, physical characteristics and elemental composition in the Milan underground transport system. *Atmos. Environ.* **2013**, *70*, 166–178. [CrossRef]
13. Li, Z.; Che, W.; Frey, H.C.; Lau, A.K.; Lin, C. Characterization of PM(2.5) exposure concentration in transport microenvironments using portable monitors. *Environ. Pollut.* **2017**, *228*, 433–442. [CrossRef] [PubMed]
14. Johansson, C.; Johansson, P. Particulate matter in the underground of Stockholm. *Atmos. Environ.* **2003**, *37*, 3–9. [CrossRef]
15. Abbasi, S.; Jansson, A.; Olander, L.; Olofsson, U.; Sellgren, U. A pin-on-disc study of the rate of airborne wear particle emissions from railway braking materials. *Wear* **2012**, *284–285*, 18–29. [CrossRef]
16. Byeon, S.H.; Willis, R.; Peters, T.M. Chemical characterization of outdoor and subway fine (PM(2.5-1.0)) and coarse (PM(10-2.5)) particulate matter in Seoul (Korea) by computer-controlled scanning electron microscopy (CCSEM). *Int. J. Env. Res. Public Health* **2015**, *12*, 2090–2104. [CrossRef] [PubMed]
17. Doiron, D.; De Hoogh, K.; Probst-Hensch, N.; Fortier, I.; Cai, Y.; De Matteis, S.; Hansell, A.L. Air pollution, lung function and COPD: Results from the population-based UK Biobank study. *Eur. Respir. J.* **2019**, *54*, 1802140. [CrossRef] [PubMed]
18. Xing, Y.-F.; Xu, Y.H.; Shi, M.H.; Lian, Y.X. The impact of $PM_{2.5}$ on the human respiratory system. *J. Thorac. Dis.* **2016**, *8*, E69–E74. [PubMed]
19. Wolf, K.; Stafoggia, M.; Cesaroni, G.; Andersen, Z.J.; Beelen, R.; Galassi, C.; Hennig, F.; Migliore, E.; Penell, J.; Ricceri, F.; et al. Long-term Exposure to Particulate Matter Constituents and the Incidence of Coronary Events in 11 European Cohorts. *Epidemiology* **2015**, *26*, 565–574. [CrossRef]
20. Du, Y.; Xu, X.; Chu, M.; Guo, Y.; Wang, J. Air particulate matter and cardiovascular disease: The epidemiological, biomedical and clinical evidence. *J. Thorac. Dis.* **2016**, *8*, E8–E19. [CrossRef]

21. Hamra, G.B.; Guha, N.; Cohen, A.; Laden, F.; Raaschou-Nielsen, O.; Samet, J.M.; Vineis, P.; Forastiere, F.; Saldiva, P.; Yorifuji, T.; et al. Outdoor Particulate Matter Exposure and Lung Cancer: A Systematic Review and Meta-Analysis. *Environ. Health Perspect.* **2014**, *122*, 906–911. [CrossRef] [PubMed]
22. Bowe, B.; Xie, Y.; Li, T.; Yan, Y.; Xian, H.; Al-Aly, Z. The 2016 global and national burden of diabetes mellitus attributable to PM 2·5 air pollution. *Lancet Planet. Health* **2018**, *2*, e301–e312. [CrossRef]
23. Mak, H.; Ng, D. Spatial and Socio-Classification of Traffic Pollutant Emissions and Associated Mortality Rates in High-Density Hong Kong via Improved Data Analytic Approaches. *Int. J. Environ. Res. Public Health* **2021**, *18*, 6532. [CrossRef]
24. Strak, M.; Janssen, N.A.; Godri, K.J.; Gosens, I.; Mudway, I.S.; Cassee, F.R.; Lebret, E.; Kelly, F.J.; Harrison, R.M.; Brunekreef, B.; et al. Respiratory Health Effects of Airborne Particulate Matter: The Role of Particle Size, Composition, and Oxidative Potential—The RAPTES Project. *Environ. Health Perspect.* **2012**, *120*, 1183–1189. [CrossRef] [PubMed]
25. Crobeddu, B.; Santiago, L.A.; Bui, L.-C.; Boland, S.; Squiban, A.B. Oxidative potential of particulate matter 2.5 as predictive indicator of cellular stress. *Environ. Pollut.* **2017**, *230*, 125–133. [CrossRef]
26. Schmid, O.; Möller, W.; Semmler-Behnke, M.; Ferron, G.A.; Karg, E.; Lipka, J.; Schulz, H.; Kreyling, W.; Stoeger, T. Dosimetry and toxicology of inhaled ultrafine particles. *Biomarkers* **2009**, *14*, 67–73. [CrossRef]
27. Kreyling, W.G.; Hirn, S.; Möller, W.; Schleh, C.; Wenk, A.; Celik, G.; Lipka, J.; Schäffler, M.; Haberl, N.; Johnston, B.D.; et al. Air–Blood Barrier Translocation of Tracheally Instilled Gold Nanoparticles Inversely Depends on Particle Size. *ACS Nano* **2013**, *8*, 222–233. [CrossRef] [PubMed]
28. Deng, Q.; Deng, L.; Miao, Y.; Guo, X.; Li, Y. Particle deposition in the human lung: Health implications of particulate matter from different sources. *Environ. Res.* **2018**, *169*, 237–245. [CrossRef]
29. Loxham, M.; Cooper, M.J.; Gerlofs-Nijland, M.E.; Cassee, F.R.; Davies, D.; Palmer, M.R.; Teagle, D.A.H. Physicochemical Characterization of Airborne Particulate Matter at a Mainline Underground Railway Station. *Environ. Sci. Technol.* **2013**, *47*, 3614–3622. [CrossRef] [PubMed]
30. Oberdörster, G. Pulmonary effects of inhaled ultrafine particles. *Int. Arch. Occup. Environ. Health* **2000**, *74*, 1–8. [CrossRef] [PubMed]
31. Chen, J.; Hoek, G. Long-term exposure to PM and all-cause and cause-specific mortality: A systematic review and meta-analysis. *Environ. Int.* **2020**, *143*, 105974. [CrossRef] [PubMed]
32. Orellano, P.; Reynoso, J.; Quaranta, N.; Bardach, A.; Ciapponi, A. Short-term exposure to particulate matter (PM_{10} and $PM_{2.5}$), nitrogen dioxide (NO_2), and ozone (O_3) and all-cause and cause-specific mortality: Systematic review and meta-analysis. *Environ. Int.* **2020**, *142*, 105876. [CrossRef] [PubMed]
33. World Health Organization. *WHO Global Air Quality Guidelines: Particulate Matter (PM2.5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*; World Health Organization: Geneva, Switzerland, 2021.
34. Choi, S.; Park, J.H.; Kim, S.Y.; Kwak, H.; Kim, D.; Lee, K.H.; Park, D.U. Characteristics of PM(2.5) and Black Carbon Exposure Among Subway Workers. *Int. J. Environ. Res. Public Health* **2019**, *16*, 2901. [CrossRef] [PubMed]
35. Plato, N.; Bigert, C.; Larsson, B.-M.; Alderling, M.; Svartengren, M.; Gustavsson, P. Exposure to Particles and Nitrogen Dioxide Among Workers in the Stockholm Underground Train System. *Saf. Health Work* **2019**, *10*, 377–383. [CrossRef]
36. Ji, W.; Liu, C.; Liu, Z.; Wang, C.; Li, X. Concentration, composition, and exposure contributions of fine particulate matter on subway concourses in China. *Environ. Pollut.* **2021**, *275*, 116627. [CrossRef]
37. Bigert, C.; Alderling, M.; Svartengren, M.; Plato, N.; de Faire, U.; Gustavsson, P. Blood markers of inflammation and coagulation and exposure to airborne particles in employees in the Stockholm underground. *Occup. Environ. Med.* **2008**, *65*, 655–658. [CrossRef]
38. Bigert, C.; Alderling, M.; Svartengren, M.; Plato, N.; Gustavsson, P. No short-term respiratory effects among particle-exposed employees in the Stockholm subway. *Scand. J. Work. Environ. Health* **2010**, *37*, 129–135. [CrossRef]
39. Loxham, M.; Nieuwenhuijsen, M.J. Health effects of particulate matter air pollution in underground railway systems—a critical review of the evidence. *Part. Fibre Toxicol.* **2019**, *16*, 12. [CrossRef]
40. ANSES. *Valeurs Limites D'exposition en Milieu Professionnel, Les Poussières Dites sans Effet Spécifique (Effets Sanitaires)*; Expertise Collective; ANSES: Maison Alfort, France, 2019; p. 6.
41. Cecala, A.B.; Chekan, G.J.; Colinet, J.; Organiscak, J.A.; Wolfe, A.L. *Best Practices for Dust Control in Metal/Nonmetal Mining*; 2013. Available online: https://www.cdc.gov/niosh/mining/userfiles/workshops/silicamnm2010/4-chekan-dustcontrolug.pdf (accessed on 23 April 2022).
42. Noble, C.A.; Vanderpool, R.W.; Peters, T.M.; McElroy, F.F.; Gemmill, D.B.; Wiener, R.W. Federal Reference and Equivalent Methods for Measuring Fine Particulate Matter. *Aerosol Sci. Technol.* **2001**, *34*, 457–464. [CrossRef]
43. Marco, G.; Bo, X. Air Quality Legislation and Standards in the European Union: Background, Status and Public Participation. *Adv. Clim. Chang. Res.* **2013**, *4*, 50–59. [CrossRef]
44. Amaral, S.S.; de Carvalho, J.A.; Costa, M.A.M.; Pinheiro, C. An Overview of Particulate Matter Measurement Instruments. *Atmosphere* **2015**, *6*, 1327–1345. [CrossRef]
45. Perera, I.E.; Litton, C.D. Quantification of Optical and Physical Properties of Combustion-Generated Carbonaceous Aerosols (<PM(2.5)) Using Analytical and Microscopic Techniques. *Fire Technol.* **2015**, *51*, 247–269. [CrossRef] [PubMed]

46. Giechaskiel, B.; Maricq, M.; Ntziachristos, L.; Dardiotis, C.; Wang, X.; Axmann, H.; Bergmann, A.; Schindler, W. Review of motor vehicle particulate emissions sampling and measurement: From smoke and filter mass to particle number. *J. Aerosol Sci.* **2014**, *67*, 48–86. [CrossRef]
47. Peters, S.; Vermeulen, R.; Olsson, A.; Van Gelder, R.; Kendzia, B.; Vincent, R.; Savary, B.; Williams, N.; Woldbæk, T.; Lavoué, J.; et al. DeveloPMent of an Exposure Measurement Database on Five Lung Carcinogens (ExpoSYN) for Quantitative Retrospective Occupational Exposure Assessment. *Ann. Occup. Hyg.* **2011**, *56*, 70–79. [CrossRef] [PubMed]
48. Peters, S.; Vermeulen, R.; Portengen, L.; Olsson, A.; Kendzia, B.; Vincent, R.; Savary, B.; Lavoué, J.; Cavallo, D.M.; Cattaneo, A.; et al. SYN-JEM: A Quantitative Job-Exposure Matrix for Five Lung Carcinogens. *Ann. Occup. Hyg.* **2016**, *60*, 795–811. [CrossRef]
49. Rajan, B.; Alesbury, R.; Carton, B.; Gerin, M.; Litske, H.; Marquart, H.; Olsen, E.; Scheffers, T.; Stamm, R.; Woldbaek, T. European Proposal for Core Information for the Storage and Exchange of Workplace Exposure Measurements on Chemical Agents. *Appl. Occup. Environ. Hyg.* **1997**, *12*, 31–39. [CrossRef]
50. Canu, I.G.; Hemmendinger, M.; Sauvain, J.J.; Suarez, G.; Hopf, N.B.; Pralong, J.A.; Ben Rayana, T.; Besançon, S.; Sakthithasan, K.; Jouannique, V.; et al. Respiratory Disease Occupational Biomonitoring Collaborative Project (ROBoCoP): A longitudinal pilot study and implementation research in the Parisian transport company. *J. Occup. Med. Toxicol.* **2021**, *16*, 22. [CrossRef]
51. Canu, I.G.; Crézé, C.; Hemmendinger, M.; Ben Rayana, T.; Besançon, S.; Jouannique, V.; Debatisse, A.; Wild, P.; Sauvain, J.; Suárez, G.; et al. Particle and metal exposure in Parisian subway: Relationship between exposure biomarkers in air, exhaled breath condensate, and urine. *Int. J. Hyg. Environ. Health* **2021**, *237*, 113837. [CrossRef]
52. Borghi, F.; Mazzucchelli, L.A.; Campagnolo, D.; Rovelli, S.; Fanti, G.; Keller, M.; Cattaneo, A.; Spinazzè, A.; Cavallo, D.M. Retrospective Exposure Assessment Methods Used in Occupational Human Health Risk Assessment: A Systematic Review. *Int. J. Environ. Res. Public Health* **2020**, *17*, 6190. [CrossRef]
53. Rodes, C.E.; Thornburg, J.W. Breathing Zone Exposure Assessment. In *Aerosols Handbook: Measurement, Dosimetry, and Health Effects*; CRC Press: Boca Raton, FL, USA, 2005; pp. 61–74.
54. Giordano, M.R.; Malings, C.; Pandis, S.N.; Presto, A.A.; McNeill, V.; Westervelt, D.M.; Beekmann, M.; Subramanian, R. From low-cost sensors to high-quality data: A summary of challenges and best practices for effectively calibrating low-cost particulate matter mass sensors. *J. Aerosol Sci.* **2021**, *158*, 105833. [CrossRef]
55. Pétremand, R.; Wild, P.; Crézé, C.; Suarez, G.; Besançon, S.; Jouannique, V.; Debatisse, A.; Canu, I.G. Application of the Bayesian spline method to analyze real-time measurements of ultrafine particle concentration in the Parisian subway. *Environ. Int.* **2021**, *156*, 106773. [CrossRef] [PubMed]
56. Ben Rayana, T.; Hemmendinger, M.; Crézé, C.; Wild, P.; Sauvain, J.-J.; Suarez, G.; Besançon, S.; Méthy, N.; Sakthithasan, K.; Carillo, G.; et al. Analyse exploratoire des mesures de particules ultrafines en temps réel dans des enceintes ferroviaires souterraines de transport public. *Arch. Mal. Prof. l'Environ.* **2022**, *83*, 159–170. [CrossRef]
57. Pétremand, R.; Suárez, G.; Besançon, S.; Dil, J.H.; Canu, I.G. A Real-Time Comparison of Four Particulate Matter Size Fractions in the Personal Breathing Zone of Paris Subway Workers: A Six-Week Prospective Study. *Sustainability* **2022**, *14*, 5999. [CrossRef]
58. Van Ryswyk, K.; Kulka, R.; Marro, L.; Yang, D.; Toma, E.; Mehta, L.; McNeil-Taboika, L.; Evans, G.J. Impacts of Subway System Modifications on Air Quality in Subway Platforms and Trains. *Environ. Sci. Technol.* **2021**, *55*, 11133–11143. [CrossRef] [PubMed]
59. Fischer, H.J.; Vergara, X.P.; Yost, M.; Silva, M.; Lombardi, D.A.; Kheifets, L. Developing a job-exposure matrix with exposure uncertainty from expert elicitation and data modeling. *J. Expo. Sci. Environ. Epidemiol.* **2015**, *27*, 7–15. [CrossRef]
60. Dahmann, D.; Taeger, D.; Kappler, M.; Büchte, S.; Morfeld, P.; Brüning, T.; Pesch, B. Assessment of exposure in epidemiological studies: The example of silica dust. *J. Expo. Sci. Environ. Epidemiol.* **2007**, *18*, 452–461. [CrossRef]
61. Campagna, D.; Randon, A.; Ihaddadene, K.; Marchand, J.L.; Mattei, N.; Imbernon, E.; Goldberg, M. Mortality Among Paris Public Transportation Workers: The EDGAR-Cohort, Preliminary Results. *Epidemiology* **2006**, *17*, S509–S510. [CrossRef]
62. de Vocht, F.; Sobala, W.; Peplonska, B.; Wilczynska, U.; Gromiec, J.; Szeszenia-Dabrowska, N.; Kromhout, H. Elaboration of a quantitative job-exposure matrix for historical exposure to airborne exposures in the Polish rubber industry. *Am. J. Ind. Med.* **2008**, *51*, 852–860. [CrossRef]
63. Noth, E.M.; Dixon-Ernst, C.; Liu, S.; Cantley, L.; Tessier-Sherman, B.; Eisen, E.A.; Cullen, M.R.; Hammond, S.K. DeveloPMent of a job-exposure matrix for exposure to total and fine particulate matter in the aluminum industry. *J. Expo. Sci. Environ. Epidemiol.* **2013**, *24*, 89–99. [CrossRef]
64. Plato, N.; Lewné, M.; Gustavsson, P. A historical job-exposure matrix for occupational exposure to diesel exhaust using elemental carbon as an indicator of exposure. *Arch. Environ. Occup. Health* **2020**, *75*, 321–332. [CrossRef]
65. Feletto, E.; Kovalevskiy, E.V.; Schonfeld, S.J.; Moissonnier, M.; Olsson, A.; Kashanskiy, S.V.; Ostroumova, E.; Bukhtiyarov, I.V.; Schüz, J.; Kromhout, H. Developing a company-specific job exposure matrix for the Asbest Chrysotile Cohort Study. *Occup. Environ. Med.* **2021**, *79*, 339–346. [CrossRef] [PubMed]
66. Johnson, C.Y.; Rocheleau, C.M.; Hein, M.J.; Waters, M.A.; Stewart, P.A.; Lawson, C.C.; Reefhuis, J. The National Birth Defects Prevention Study Agreement between two methods for retrospective assessment of occupational exposure intensity to six chlorinated solvents: Data from The National Birth Defects Prevention Study. *J. Occup. Environ. Hyg.* **2017**, *14*, 389–396. [CrossRef] [PubMed]