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Occupational exposure to particulate matter and staff sickness absence on the London underground

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ABSTRACT

The London Underground (LU) employs over 19,000 staff, some of whom are exposed to elevated concentrations of particulate matter (PM) within the network. This study quantified the occupational exposure of LU staff to subway PM and investigated the possible association with sickness absence (SA).

A job exposure matrix to quantify subway $PM_{2.5}$ staff exposure was developed by undertaking measurement campaigns across the LU network. The association between exposure and SA was evaluated using zero-inflated mixed-effects negative binomial models.

Staff $PM_{2.5}$ exposure varied by job grade and tasks undertaken. Drivers had the highest exposure over a work shift (mean: 261 $\mu g/m^3$), but concentrations varied significantly by LU line and time the train spent subway.

Office staff work in office buildings separate to the LU network and are unexposed to occupational subway $PM_{2.5}$. They were found to have lower rates of all-cause and respiratory infection SA compared to non-office staff, those who work across the LU network and are occupational exposed to subway $PM_{2.5}$. Train drivers on five out of eight lines showed higher rates of all-cause SA, but no dose–response relationship was seen. Only drivers from one line showed higher rates of SAs from respiratory infections (incidence rate ratio: 1.24, 95% confidence interval 1.10–1.39). Lower-grade customer service (CS) staff showed higher rates of all-cause and respiratory infection SA compared to higher grade CS staff. Doctor-certified chronic respiratory and cardiovascular SAs were associated with occupational $PM_{2.5}$ exposure in CS staff and drivers.

While some groups with higher occupational exposure to subway PM reported higher rates of SA, no evidence suggests that subway PM is the main contributing factor to SA. This is the largest subway study on health effects of occupational $PM_{2.5}$ exposure and may have wider implications for subway workers, contributing to safer working environments.

1. Introduction

The London Underground (LU) opened in 1863 and is the oldest underground transport system in the world. It consists of 272 stations, 45 % of which are underground. The network provides around 2.8 million journeys a day to those travelling in London (Transport for London, 2018) and employs over 19,000 staff (Transport for London, 2020a). Some of these staff are exposed to elevated concentrations of particulate matter (PM) due to emissions within the network (subway PM). The adverse health effects of outdoor PM air pollution have been widely studied and are known to contribute to increases in mortality and morbidity (Pope, 1989). However, personal exposure based on time spent in different environments can vary from outdoor PM concentrations, and the health effects of PM from other environments are less well understood (Evangelopoulos et al., 2020; Loxham & Nieuwenhuijsen, 2019). One such environment is the LU, where PM differs in both

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physical and chemical composition to outdoor PM.

Smith et al's measurement campaign found that although mean subway $PM_{2.5}$ mass was around 15 times greater (302 μg/m^3) than at background (18 μg/m^3) or roadside sites (26 μg/m^3) in London, particle number counts (PNC) were lower (subway 15,070 particles/cm^3, roadside 26,801 particles/cm^3), and the mean particle diameter was greater (subway 77 nm, roadside 55 nm). Smaller particles are generally considered more hazardous, as they penetrate deeper into the airways and allow a greater surface area for free radical reactions; and therefore are more likely to induce lung inflammation and tissue damage. The lower PNC and larger particle size may indicate that, despite a higher mass concentration, there are likely to be fewer health effects associated with subway PM compared to ambient PM (Mantecca et al., 2010; Tao et al., 2003).

Apart from physical differences, there are also differences in chemical composition. In the LU, Fe_2O_3 made up 47 % of $PM_{2.5}$ mass (Smith et al., 2020b). In contrast, $PM_{2.5}$ sampled at a roadside site in the UK was made up of just 6 % iron rich dust (Harrison et al., 2004). On the LU, there is an abundance of metallic components, such as steel (tyreless) wheels and rails, cast-iron collector shoes, and silica brake pads, all of which are constantly in frictional contact (COMEAP, 2019)The increased concentrations of iron are seen consistently in subway systems around the world (Chang et al., 2021). There are also fewer combustion particles of the type commonly found in the ambient atmosphere from traffic and wood burning (NAEI, 2019). Exposure to excess amounts of iron and other transition metals cause adverse health effects due to redox reactions, inflammation, oxidative stress, and DNA strand damage (Kelly & Fussell, 2012).

A previous study by Smith et al (2020) found $PM_{2.5}$ concentrations on the LU network ranging from 4 to 885 μg/m^3. Historical annual personal measurements of respirable particles ($PM_{4.25}$) made by Transport for London (TfL) in drivers' cabs ranged from 20 to 1810 μg/m^3 (Transport for London, 2022) and were found to be below UK regulatory limits (HSE, 2013).

To date, any health effects of exposure to subway PM has been difficult to establish due to conflicting evidence between epidemiological, *in vivo* and *in vitro* studies. *In vivo* studies have lacked clear evidence on both short- and long-term exposure to subway PM, and some are underpowered. While some epidemiological studies found increased levels of inflammatory blood and urinary biomarkers among highly exposed subway workers when compared to non-subway workers or less exposed subway workers in Stockholm, New York City, and Tehran, the clinical significance of these results is uncertain, as it is unclear whether increased levels of inflammatory biomarkers resulted in health outcomes after prolonged occupational exposure to subway PM. Apart from changes in biomarkers, these studies did not find an association between subway PM exposure and markers of cardiovascular health, such as heart rate variability and lung function. In a case-crossover study, health volunteers in New York were exposed to subway PM in one of the most polluted subway stations, and a location with low PM concentration for 2 h each (Luglio, 2023). There were no significant differences in changes to blood pressure, heart rate variability, and various lung function tests based on the exposure. However, after the subway visit, symptoms such as headaches, sore throat, cough, and chest tightness were worse compared to the visit to the clean location.

Meanwhile, *in vitro* studies indicate PM from the LU may be more genotoxic, elicit more reactive oxygen species generation, and induce greater levels of oxidative stress compared to ambient PM (Loxham & Nieuwenhuijsen, 2019). Human nasal and epithelial cells exposed to PM_{10} from the LU showed increased pneumococcal adhesion (Miyashita et al., 2022).

The UK Committee on the Medical Effects of Air Pollutants (COMEAP) reviewed the available evidence and concluded that "much work is still needed to investigate the relationship between subway PM exposure and any health effects" (COMEAP, 2019). They also highlighted the value of research into LU workforce health who often face higher exposures than the travelling public, and in whom any associated health risks may be more readily apparent. This study aims to quantify occupational exposure of LU staff to subway PM and analyse whether exposure is associated with sickness absences (SAs) in a retrospective cohort.

2. Methods

2.1. Study design and population

A pseudonymised dataset containing occupational and demographic traits of TfL staff employed between 1 January 2014 and 31 December 2019, including those who joined or left during this period, was constructed from two independent datasets provided by TfL.

The initial cohort consisted of 50,542 TfL staff. Staff were excluded if they had any missing data in respect to sex, age, job, or employment duration.

Working with human resources (HR), occupational health, and expert users within TfL, all staff job positions (n = 10,016) were grouped into 14 categories, based on job descriptions and locations of work (Table 1). The analysis of SAs was restricted to TfL staff with regular occupational exposure to subway $PM_{2.5}$. Staff not exposed to subway PM, but exposed to PM from other occupational activities (e.g. bus drivers, carpenters, welders) were excluded. Non-operational office-based staff were retained within the dataset as a comparator group unexposed to subway PM during their working day. Staff who wore breathing apparatus while working were excluded, as their exposure to subway PM could not be assessed accurately.

2.2. Quantifying occupational exposure

To quantify location specific exposure and populate a job exposure matrix, measurement campaigns were conducted to monitor $PM_{2.5}$ exposure levels of staff throughout their working day based on a detailed survey of working practices. Personal measurements were taken for 21 drivers over seven LU lines, and 30 CS staff were involved in microenvironment sampling across 15 LU stations. Light scattering laser photometers (Sidepak AM520 & AM510, TSI Inc, USA) fitted with $PM_{2.5}$ impactors, were used to measure $PM_{2.5}$ mass at a 1-second resolution for personal exposure measurements and location surveys. Data was calibrated against a filter-based reference instrument on a per instrument basis as described in Smith et al. (2020) using scaling factors derived in a high concentration subway PM environment and an outdoor environment.

LU drivers are operationally allocated to individual lines due to different rolling stock, depot locations, and track signalling patterns and so drivers generally remain on a single line. Smith et al. (2020) demonstrated that passenger exposure was lower and similar for the Hammersmith and City, Circle, District, and Metropolitan lines (median concs 4 – 8 μg/m^3). This group of low exposure lines share track, similar rolling stock, and their journeys are characterised by long outdoor periods and generally shallow tunnels. The Circle line was chosen as being representative of driver exposure on the low exposure lines; drivers were assessed for each of the other lines individually. Three drivers per line were equipped with a TSI Sidepak for 1–5 h of their shift. The inlet was attached to each driver's shirt collar to sample in their breathing zone. Time-weighted averages for drivers on each line were extrapolated using time-activity diaries; measurements taken while drivers are on their meal breaks are excluded from overall exposure. Historic $PM_{2.5}$ exposures of drivers were also measured by TfL in five campaigns between 2014 and 2019. 55 total measurements were taken by TfL during this period across all LU lines, with measurements running for approximately 3–6 h (Transport for London, 2022). Measurements made by TfL were collected by gravimetric analysis on glass fibre filters, with $PM_{2.5}$ inlets fitted onto cyclone samplers. The mean of all 55 historical and 21 modern measurements was used to quantify driver exposure.

Table 1
Transport for London (TfL) staff groups and whether they were included or excluded in the cohort.

Job group	Number of staff	Job description	Included	Reason for exclusion
Train drivers	4,842	Operate trains within the LU tunnels, tracks, and depots	Yes	–
CSA – non-office based	5,996	Customer-facing staff in LU stations, reports to customer service managers and supervisors. Assists passengers with their journeys	Yes	–
CSM – office based	3,127	Customer-facing staff in LU stations, leads teams of customer service assistants. Provide operational support for the LU stations	Yes	–
Track staff	2,159	Repair, maintain, and clean both the below and above ground sections of track within the LU network	No	Occupational exposure to non-subway PM, use of breathing apparatus when working
Fleet staff	1,726	Maintain and repair the various rolling stock operating throughout the LU network	Yes	–
Operational – others	1,123	Involved in the operational aspects of TfL that do not fit any of the other job groups	No	Occupational exposure to non-subway PM
Stations – other	623	Asset maintenance staff working in stations, such as lifts and escalator teams	No	Occupational exposure to non-subway PM
Non-operational engineers	143	Work in a wider range of areas in TfL, such as mechanical, business, civil, and structure, etc	No	Occupational exposure to non-subway PM
Non-operational – other	575	Work in non-customer facing roles across TfL and LU	No	Occupational exposure to non-subway PM
Surface operational – river	13	Involved in running the river transport services in London	No	Occupational exposure to non-subway PM
Surface operational – car drivers	481	Drive accessible vehicles for vulnerable people in London who cannot easily access public transport	No	Occupational exposure to non-subway PM
Surface operational – other	1,358	Involved in operating other aspects of above-ground transportation in London	No	Occupational exposure to non-subway PM
Left the company	12,171	Retired, or left employment	No	No job information provided
Non-operational – office only	16,209	Cover a wide range of jobs, such as accountants, HR, etc, however are all performed in office buildings separate to the LU network	Yes	–

CSA, customer service assistant; CSM, customer service manag.

The $PM_{2.5}$ exposure of customer service (CS) staff was based on a series of network-wide measurements. $PM_{2.5}$ mass concentration was measured at all the undergrounds platforms in the LU network and at the three subsequent stations (out of tunnel/above ground) for a minimum of 5 min. Fifteen representative stations were selected, with a range of $PM_{2.5}$ concentrations, for further in-station sampling. In each of the selected stations, $PM_{2.5}$ concentrations were measured in microenvironments where CS staff work throughout the day – the staff office, ticket hall, and the confines of the station, for 30–60 min each. To conduct microenvironment sampling, a Sidepak was provided to a CSM in the office, who remained stationary in the office for 30–60 min. A second Sidepak was given to a CSA who was working in the ticket hall and remained in the ticket hall for 30–60 min, and a third Sidepak remained with the researcher, who walks around the confines of the station for 30–60 min.

The exposure of CS staff depends on their daily work routines, which changes based on the location of the station as well as the staff's grade. TfL groups LU stations into security levels, depending on the passenger flow and notable landmarks around the station. Security levels dictate the frequency of security checks that must be conducted throughout the station, and the length of time spent performing platform duties. To better understand daily staff routines, 116 CS staff from 55 stations were interviewed to determine how much time was spent in different microenvironments in each station and develop time activity diaries. This was used along with the stationary measurements conducted to extrapolate CS exposure. All LU stations were grouped into tertiles – low, medium, or high pollution, based on CS exposure.

2.3. Calibration and correction

Due to variations in the physicochemical properties of outdoor and underground PM, such as refractive index, shape, and density, laser photometers are known to require calibration when working within these different environments (Smith et al., 2020a). To generate suitable scaling factors, the Sidepaks were co-located for 50 h continuously alongside a reference filter-based sampler (Partisol 2025, Thermo Fisher Scientific Inc, USA) on the platform of the northbound Northern Line at the Hampstead underground station. This is the deepest station on the network and provides a high concentration of subway PM and consequently the lowest possible contribution of outdoor PM and has been used in previous studies (Saunders et al., 2019; Seaton et al., 2005; Smith et al., 2020a). A similar comparison was made between the Sidepaks and an outdoor reference instrument (Fidas 200E, Palas GmbH, DE) at the Honor Oak Park Automatic Urban and Rural Network (AURN) background reference monitoring station (location 51,4496, −0.0374). Correction factors were derived for both underground and above ground $PM_{2.5}$ by comparing the mass of $PM_{2.5}$ mass measured by the reference instruments and the mass concentration measured by the Sidepaks using a Deming regression (Wu & Yu, 2018). The correction factors were applied proportionally to the Sidepak $PM_{2.5}$ measurement, assuming a time-matched background contribution to subway concentrations as per Smith et al (2020), throughout the measurement campaign (SI Table 1, SI Figs. 1–3).

2.4. Sickness absence records

Pseudonymised SA data were provided by TfL Human Resources Department. Within the TfL database, each SA was recorded as one of 800 SA codes. For this study, 111 codes (25 respiratory infection, 30 respiratory non-infection and 56 cardiovascular), which accurately reflect diseases with known associations or causal pathways linked to PM and air pollution were extracted (Chen & Hoek, 2020). All other SA episodes were coded as "other" to maintain higher levels of confidentiality. The start and end dates and cause were provided for each SA episode.

2.5. Statistical analysis

Incidence rate ratios (IRRs) were estimated for each exposure category using a zero-inflated mixed-effects negative binomial model, which accounted for over-dispersion and excess zeros, with a random effect for each staff member. Models were adjusted for age, sex, employment duration, and annual outdoor $PM_{2.5}$ and NO_2. Annual mean $PM_{2.5}$ and NO_2 concentrations were derived to represent urban background environment in central (Bloomsbury) and outer (North Kensington) London. CS staff were assigned to central or outer London stations depending on their station area location. Drivers and engineers were assigned outer London outdoor pollution concentrations due to the location of their depots; office workers were assigned inner London outdoor pollution concentrations.

To account for different rates of transmission in respiratory infections, and various stress levels, models looking at CS staff further adjusted for passenger density at stations, using the passenger "tap-in and tap-out" data (2014–2019) from the London Datastore. Annual means were calculated for each station area, and grouped into tertiles based on mean passenger density (Transport for London, 2020b, 2021).

SA data were examined for all recorded episodes, and for subgroups: respiratory infections, non-infectious respiratory, and cardiovascular codes.

Sensitivity analyses were performed by examining non-respiratory and cardiovascular causes of SA to determine the main driving factor of total SAs. Age-stratified analyses were performed to determine the impact of employment duration. To adjust for systematic differences between individuals, a variable was created for each individual using the total number of SA episodes in the study period. This acted as a proxy for an individual's propensity to take SA and to inform of absenteeism behaviour. Additional sensitivity analyses were performed by stratifying SAs by duration to check for reliability of SA reporting and the robustness of the estimates. SAs fewer than 7 calendar days are self-certified, while SAs 7 calendar days or longer are doctor certified.

All statistical analyses were carried out with R software (version 4.2.2).

Ethical approval

This study was approved by the Imperial College Research Ethics Committee and Research Governance and Integrity Team (ICREC reference number: 21IC7231).

3. Results

3.1. Cohort characteristics

Data were missing on 13,893 staff; 6,762 were excluded due to no exposure to, or additional occupational exposure to, subway $PM_{2.5}$. The final cohort comprised 29,744 staff (27.5 % female) of whom 86.6 % were aged under 60 (at 31/12/2019) and 41.1 % were employed for 5–14 years (by 31/12/2019). 52.2 % had office jobs, 27.6 % were CS staff, and 14.4 % were train drivers (Table 2). 20 % of the cohort had no SA episodes since 2014, and 68.8 % had between 1 and 10 sickness absences over the study period. There were 136,739 episodes of all-cause SAs, with 34,045 respiratory infection episodes, 2,860 non-infectious respiratory episodes, and 1,676 cardiovascular episodes.

Table 2
Characteristics of the study population.

Variable	Frequency of risk factor in study sample	
	N = 29,744	% [a]
Sex		
Female	8,182	27.5
Male	21,562	72.5
Age [b]		
<30	3,160	10.6
30–39	7,395	24.8
40–49	7,398	24.9
50–59	7,828	26.3
>60	3,963	13.4
Job position [b]		
Office	15,519	52.2
Fleet [c]	1,722	5.8
Customer service agents and managers	8,222	27.6
Driver	4,281	14.4
Employment duration (years) [b]		
<5	9,892	33.2
5–9	4,458	15.0
10–14	7,901	26.1
>14	7,493	25.2
Sickness absence episodes between 1 January 2014 and 31 December 2019		
0	5,983	20.1
1–2	7,315	24.6
3–4	5,186	17.4
5–6	3,652	12.3
7–8	2,628	8.8
9–10	1,690	5.7
>10	3,290	11.1

[a] Prevalence % in total study sample (N = 29,744).
[b] On 31 December 2019.
[c] Fleet. fleet staff working on maintaining the LU rolling stock at various depots around London.

3.2. Exposure outcomes

$PM_{2.5}$ exposure amongst drivers varied from 72 μg/m^3 (District line) to 787 μg/m^3 (Piccadilly line) (Table 3). Customer service assistants (CSAs) (17–310 μg/m^3) had higher exposure to $PM_{2.5}$ than customer service managers (CSMs) (9–154 μg/m^3), largely due to duration of time spent on station platforms.

3.3. Sickness absence outcome

Fleet staff, CS staff, and drivers had higher rates of all-cause SAs compared to non-exposed office workers (Table 4). For respiratory infections, higher rates of reported SA in the higher PM exposed fleet staff (IRR 1.10, 95 % CI 1.02, 1.19), CS staff (IRR 1.10, 95 % CI 1.06, 1.14), and drivers (IRR 1.12, 95 % CI 1.07, 1.18) compared to office workers were seen. Fleet staff had a lower rate of non-infectious respiratory SAs compared to office workers (IRR 0.49, 95 % CI 0.30, 0.81). SA due to non-infectious respiratory disease was not associated with any other job groups, and cardiovascular disease were not associated with any job group.

3.4. Drivers

Five of the eight driver sub-groups had significantly greater all-cause

Table 3
Measurements of London Underground particulate matter exposure of the occupational cohort.

	Number of staff	Historical PM2.5 mean μg/m^3	Historical range $PM_{2.5}$ IQR (25th %ile, 75th %ile) μg/m^3	2022 $PM_{2.5}$ mean μg/m^3	2022 range $PM_{2.5}$ IQR (25th %ile, 75th %ile) μg/m^3	Overall study mean $PM_{2.5}$ (μg/m^3)
Driver						
District	666	77	100 (25, 125)	63	45 (22, 67)	72
Circle and Hammersmith & City	224	86	65 (40, 105)	63	45 (22, 67)	75
Metropolitan	341	86	65 (40, 105)	63	45 (22, 67)	75
Jubilee	462	165	149 (71, 220)	153	214 (27, 241)	160
Victoria	331	242	92 (168, 260)	387	198 (278, 476)	271
Central	581	222	165 (140, 305)	130	248 (10, 258)	198
Northern	729	260	150 (155, 305)	205	313 (19, 332)	255
Bakerloo	237	306	117 (198, 315)	158	111 (98, 209)	286
Piccadilly	710	889	870 (165, 1035)	148	170 (39, 209)	787
CSM						
Low	1,205	No measurements taken		9	7 (3, 10)	9
Medium	653	No measurements taken		67	31 (44, 75)	67
High	368	No measurements taken		154	2 (152, 154)	154
CSA						
Low	1,822	No measurements taken		17	12 (5, 17)	17
Medium	2,595	No measurements taken		117	71 (81, 152)	117
High	1,579	No measurements taken		310	16 (296, 312)	310
Fleet						
NA	1,722	No measurements taken				
Office						
NA	15,519	No measurements taken				

CSM, customer service manager; CSA, customer service assistant.

Table 4
Associations of staff grouped by job positions with incidence rate ratios (IRR) of sickness absence episodes from 1 January 2014 to 31 December 2019.

Sickness absence	Job group	IRR (95 % CI) [‡]
All-cause	Office	Reference
	Fleet	1.39 (1.32, 1.47) *
	CS	1.33 (1.29, 1.37) *
	Driver	1.60 (1.55, 1.66) *
Non-infectious respiratory	Office	Reference
	Fleet	0.49 (0.30, 0.81) *
	CS	0.83 (0.67, 1.02)
	Driver	0.82 (0.64, 1.05)
Cardiovascular	Office	Reference
	Fleet	0.77 (0.39, 1.52)
	CS	1.26 (0.93, 1.71)
	Driver	0.80 (0.53, 1.19)
Respiratory infection	Office	Reference
	Fleet	1.10 (1.02, 1.19) *
	CS	1.10 (1.06, 1.14) *
	Driver	1.12 (1.07, 1.18) *

IRR, incidence rate ratio; CI, confidence interval; (*p < 0.05); CS, customer service.
[‡] Model adjusted for position + sex + age + employment duration + outdoor $PM_{2.5}$ + outdoor NO_2.

Table 5
Associations of drivers grouped by line with incidence rate ratios (IRR) of sickness absence episodes from 1 January 2014 to 31 December 2019.

Sickness absence	Underground line	IRR (95 % CI) [‡]
All-cause	District	Reference
	Metropolitan	(0.93, 1.10)
	Circle and H&C	1.37 (1.25, 1.50) *
	Jubilee	1.26 (1.17, 1.36) *
	Central	1.21 (1.12, 1.30) *
	Northern	1.11 (1.04, 1.19) *
	Victoria	1.09 (1.00, 1.19)
	Bakerloo	1.09 (0.99, 1.20)
	Piccadilly	1.18 (1.10, 1.27) *
Non-infectious respiratory	District	Reference
	Metropolitan	1.25 (0.62, 2.51)
	Circle and H&C	1.46 (0.66, 3.22)
	Jubilee	1.46 (0.76, 2.80)
	Central	0.87 (0.45, 1.70)
	Northern	0.83 (0.44, 1.55)
	Victoria	1.24 (0.59, 2.59)
	Bakerloo	1.05 (0.44, 2.51)
	Piccadilly	0.93 (0.48, 1.79)
Cardiovascular	District	Reference
	Metropolitan	1.46 (0.50, 4.24)
	Circle and H&C	1.13 (0.32, 3.92)
	Jubilee	1.12 (0.40, 3.17)
	Central	0.97 (0.35, 2.63)
	Northern	1.36 (0.55, 3.38)
	Victoria	1.56 (0.52, 4.73)
	Bakerloo	0.60 (0.10, 3.45)
	Piccadilly	1.24 (0.49, 3.17)
Respiratory infection	District	Reference
	Metropolitan	0.90 (0.78, 1.03)
	Circle and H&C	1.13 (0.97, 1.32)
	Jubilee	1.11 (0.98, 1.26)
	Central	1.24 (1.10, 1.39) *
	Northern	1.03 (0.92, 1.16)
	Victoria	0.92 (0.80, 1.07)
	Bakerloo	1.11 (0.95, 1.29)
	Piccadilly	1.01 (0.89, 1.13)

IRR, incidence rate ratio; CI, confidence interval; (*p < 0.05); H&C, Hammersmith and City.
[‡] Model adjusted for position + sex + age + employment duration + outdoor $PM_{2.5}$ + outdoor NO_2.

SAs compared to District line drivers (Table 5) but there was no exposure response relationship. Only Central line drivers had a significantly higher rate of respiratory infections (IRR 1.24 (95 % CI 1.10, 1.39). Non-infectious respiratory and cardiovascular SAs were not associated with subway PM exposure.

3.5. Customer service staff

Compared with CSM, CSA had higher rates of all-cause SA (IRR 1.25, 95 % CI 1.20, 1.29) and respiratory infections (IRR 1.23, 95 % CI 1.16, 1.30) (Table 6). There was no association between job group and non-infectious respiratory or cardiovascular SAs.

Only CSAs had significantly increased rates of SAs for respiratory infections compared to the CS staff with the lowest exposure to $PM_{2.5}$ concentrations (Table 7). There was no evidence that CSMs working in stations with higher $PM_{2.5}$ concentrations had increased rates of

Table 6
Associations of customer service staff grouped by job with incidence rate ratios (IRR) of sickness absence episodes from 1 January 2014 to 31 December 2019.

Sickness absence	Customer service staff grade	IRR (95 % CI) ‡
All-cause	CSM	Reference
	CSA	1.25 (1.20, 1.29) *
Non-infectious respiratory	CSM	Reference
	CSA	1.17 (0.86, 1.60)
Cardiovascular	CSM	Reference
	CSA	1.02 (0.71, 1.46)
Respiratory infection	CSM	Reference
	CSA	1.23 (1.16, 1.30) *

IRR, incidence rate ratio; CI, confidence interval; (*p < 0.05); CSM, customer service manager; CSA, customer service assistant.
‡ Model adjusted for position + sex + age + employment duration + outdoor $PM_{2.5}$ + outdoor NO_2 + passenger density.

Table 7
Associations of customer service staff grouped by job and location of stations with incidence rate ratios (IRR) of sickness absence episodes from 1 January 2014 to 31 December 2019.

Sickness absence	Customer service staff based on tertile of their station PM concentration	IRR (95 % CI) ‡
All-cause	CSM low	Reference
	CSM medium	1.12 (1.06, 1.19) *
	CSM high	1.12 (1.04, 1.20) *
	CSA low	1.24 (1.18, 1.30) *
	CSA medium	1.35 (1.29, 1.42) *
	CSA high	1.35 (1.28, 1.43) *
Non-infectious respiratory	CSM low	Reference
	CSM medium	1.12 (0.69, 1.85)
	CSM high	1.11 (0.57, 2.16)
	CSA low	1.14 (0.77, 1.70)
	CSA medium	1.37 (0.90, 2.09)
	CSA high	1.09 (0.65, 1.82)
Cardiovascular	CSM low	Reference
	CSM medium	1.38 (0.81, 2.35)
	CSM high	0.96 (0.50, 1.86)
	CSA low	0.94 (0.59, 1.51)
	CSA medium	1.34 (0.82, 2.20)
	CSA high	1.00 (0.54, 1.83)
Respiratory infection	CSM low	Reference
	CSM medium	1.05 (0.95, 1.16)
	CSM high	0.98 (0.87, 1.11)
	CSA low	1.28 (1.18, 1.39) *
	CSA medium	1.23 (1.13, 1.34) *
	CSA high	1.19 (1.08, 1.31) *

IRR, incidence rate ratio; CI, confidence interval; (*p < 0.05); CSM, customer service manager; CSA, customer service assistant; low, stations with lowest PM concentrations; medium, stations with medium PM concentrations; high, stations with highest PM concentrations.
‡ Model adjusted for position + sex + age + employment duration + outdoor $PM_{2.5}$ + outdoor NO_2 + passenger density.

respiratory infections, compared to those in stations with low $PM_{2.5}$ concentrations. Finally, non-infectious respiratory and cardiovascular SAs were not found to be associated with CS $PM_{2.5}$ exposure.

Sensitivity analyses showed no meaningful differences in rates for all-cause SA and non-respiratory or cardiovascular SAs. This suggests that respiratory infections are not the main driving force behind the trends seen in all-causes of SAs, with other unknown causes contributing to the increased rates of SAs seen across the cohort (SI Table 3). When comparing the age-stratified groups, no material changes were seen to the main results (SI Table 4). Length of employment duration was found to be positively associated with all-cause SA rates in employees below the age of 60, and respiratory infections SA for those below the age of 50. Duration of employment was not seen to be associated with non-infectious respiratory and cardiovascular SA.

After adjusting for individuals' propensity to take sick leave, drivers were less likely to report SA compared to other job positions (SI Table 5).

Restricting the analyses to doctor-certified SAs did not result in a significant change to IRRs for all-causes of SAs and respiratory infection SAs, all three job groups showed significantly increased rates compared to office staff (Table 8). When looking at non-infectious respiratory SAs, CS staff and drivers showed significantly higher rates of SAs compared to office staff, which differed to results seen from all lengths of SAs (Table 4). CS staff had significantly higher rates of cardiovascular SAs compared to office staff (Table 8).

4. Discussion

This is the first study to assess a wide range of LU staff's exposure to subway PM and is more extensive than previous studies undertaken (Seaton et al., 2005) both spatially and temporally. It drew upon new measurements of CS staff and driver exposure, and historic TfL driver exposure measurements from 2016 to 2021. Exposure of TfL staff to subway PM was found to be highly heterogeneous across the cohort and job groups. Even amongst the same job role, exposure depended largely

Table 8
Associations of staff grouped by job positions with incidence rate ratios (IRR) of doctor-certified sickness absence episodes from 1 January 2014 to 31 December 2019.

Sickness absence	Exposure category	IRR (95 % CI) ‡
All-cause – doctor certified	Office	Reference
	Fleet	2.66 (2.44, 2.89) *
	CS	2.35 (2.26, 2.47) *
	Driver	2.97 (2.82, 3.14) *
Non-infectious respiratory – doctor certified	Office	Reference
	Fleet	1.71 (0.53, 5.55)
	CS	2.17 (1.24, 3.81) *
	Driver	2.02 (1.07, 3.84) *
Cardiovascular – doctor certified	Office	Reference
	Fleet	0.99 (0.41, 2.42)
	CS	1.61 (1.05, 2.46) *
	Driver	0.97 (0.57, 1.63)
Respiratory infections – doctor certified	Office	Reference
	Fleet	2.56 (2.01, 3.26) *
	CS	2.95 (2.61, 3.33) *
	Driver	3.34 (2.88, 3.88) *

IRR, incidence rate ratio; CI, confidence interval; (*p < 0.05); CS, customer service.
‡ Model adjusted for position + sex + age + employment duration + outdoor $PM_{2.5}$ + outdoor NO_2.

upon the work location.

4.1. Exposure assessments

Occupational exposure limits dictated by the Health and Safety Executive (HSE) are set at inhalable (PM_{100}) and respirable ($PM_{4.25}$) dust size fractions, while measurements conducted in this study were made in $PM_{2.5}$ size fractions. The work exposure limit for 8-hour time weighted average of respirable dust is 4 mg/m^3 (HSE, 2013). Because of differences in size fractions, it is difficult to compare our $PM_{2.5}$ measurements to the HSE legal limits. In previous measurements by TfL, respirable dust and $PM_{2.5}$ were taken together and concentrations of $PM_{2.5}$ were approximately 48–94 % that of respirable dust (Transport for London, 2022). Assuming a similar ratio for our measurements, the exposures would lie under the HSE legal limits. Historical TfL respirable dust measurements show they do not exceed HSE exposure limits (Transport for London, 2022).

For drivers, there was a wide range in exposure between lines. Drivers with lower $PM_{2.5}$ exposure worked on lines with shallow tunnels, a higher proportion of the track above ground and with rolling stock introduced after 2010. Drivers experiencing the highest exposure to $PM_{2.5}$ worked on lines with deeper tunnels, with more of their time spent underground; this rolling stock tended to be older (1972–1973). Similar to previously reported passenger exposures (Smith et al., 2020a), the District exposures were the lowest, followed in increasing $PM_{2.5}$ concentration by Hammersmith & City, Circle, Jubilee, Central, Metropolitan, Piccadilly, Bakerloo, Northern, and Victoria (SI Table 2). In this study, the mean exposures increased in a slightly different order, with District, Hammersmith & City, Circle, Metropolitan, Jubilee, Victoria, Central, Northern, Bakerloo, and Piccadilly. This may be a result of variations in air exchange between the passenger cars and driver cabins or some driver preferences and behaviours that can skew exposure estimates, e.g. driving with open windows. It is also worth noting that driver exposure measurements made for this study in 2022 were lower than historical TfL measurements. This may reflect a more widespread reduction in concentrations on the network reported by TfL (London, 2021) in part due to enhanced cleaning, changes in rolling stock (Circle, District, and Hammersmith and City lines), structural refurbishments across the Jubilee, Bakerloo, Central, and Northern lines, and updates to the Central line train propulsion system (Transport for London, 2023). However, it may relate to changes in line routing between 2016 and 2022 (with different proportions of time spent above/below ground) or differences in measurement protocols between old and new studies.

These new measurements of CS staff show that CSAs have higher exposure to $PM_{2.5}$ compared to CSMs, due to their daily working routine. Furthermore, exposure varied greatly depending on station location. Underground stations and interchanges for multiple lines had higher $PM_{2.5}$ concentrations, due to higher train emissions and reduced ventilation, compared to quieter, above ground stations.

4.2. Sickness absence outcomes

When comparing staff with similar working practices, those exposed to higher concentrations of subway PM reported higher SA rates. Six out of eight driver sub-groups and all CS staff sub-groups had higher levels of all-cause SA compared to the least exposed job-matched sub-group. While this provides evidence of associations between subway PM exposure and SAs, there were no clear exposure response relationship (where increasing exposure is associated with an increasing or decreasing risk of the outcome), to support causative associations.

Operational staff were seen to have higher rates of all-cause and respiratory infection SAs compared to office staff. Associations were also seen between CS staff and drivers for doctor-certified non-infectious respiratory SAs, and between CS staff and doctor-certified cardiovascular SAs. No associations were seen for the other job groups, and for total SAs, which included both self- and doctor-certified SAs. The short follow-up time may point to an insufficient amount of time to see the development of chronic respiratory and cardiovascular diseases which may occur after prolonged inflammation as seen after exposure to subway dust in Stockholm, New York, and Tehran (Bigert et al., 2008; Grass et al., 2010; Mehrdad et al., 2015). The associations that were seen for some job groups and doctor-certified respiratory and cardiovascular SAs may be due to better diagnoses by doctors, as opposed to self-diagnosis leading to more accurate categorisation of the SA cause. It may also be more accurately recorded by the managers, compared to self-certified SAs.

The increased rates of respiratory infection SAs support recent findings in an *in vivo* mouse model demonstrating increased pneumococcal adhesion to airway cells and increased susceptibility to invasive diseases, like pneumococcal infection, following exposure to subway PM_{10} (Miyashita et al., 2022).

There was evidence in some age groups that employment duration was positively associated with all-cause and respiratory infection SAs. The association between employment duration and SA was stronger in the younger age groups, suggesting that employment duration becomes less important as workers age.

4.3. Strengths and limitations

A strength of this study was the large sample size compared with previous occupational health studies of subway workers, which ranged from 6 to 348 (Bigert et al., 2007; Grass et al., 2010; Gustavsson et al., 2008; Mehrdad et al., 2015), leading to higher statistical power, and the inclusion of both men and women. Furthermore, the measurement campaign conducted was robust and comprehensive, with well-validated methods. The use of historical measurements further contributes to the validity of the exposure assessment. Additionally, SA records were obtained for all staff of TfL employed between 2014 and 2019. This gave an unbiased and representative view of the sickness absence patterns of the cohort.

This is the first study of SA among subway workers, but SA has used in other occupational studies (Elliott et al., 2019; Marmot et al., 1995; Van Der Plaat et al., 2021) and can be more clinically relevant and easier to translate into practice than exposure associated biomarkers. However, misclassification of clinical cause for absence is possible, for example, if individuals misclassify the cause if self-certified, or data entry errors by managers. While the use of doctor-certified SAs may be a more reliable metric, it is restrictive to chronic impacts. Additionally, individual behaviour, such as presenteeism and absenteeism, underlying health diseases and workplace behavioural norms across different groups of staff could not be measured and adjusted for (Gosselin et al., 2013). This was especially pertinent when comparing TfL office staff with LU operational staff where differences in workplace norms would have been accentuated. Therefore, although LU staff had higher reported rates of SA than office staff, this result should be interpreted cautiously.

We attempted to minimise a potential healthy worker effect by performing internal comparisons to LU staff with differing levels of exposure. However, this type of selection bias cannot be completely eliminated and may result in an underestimate of the association between exposure to PM and SA rates (Chowdhury et al., 2017). While the scope of the analyses was limited to respiratory and cardiovascular SAs, PM exposure is known to be associated with other diseases not detailed in this study, such as stroke or diabetes (Pearson et al., 2010; Scheers et al., 2015). It is therefore unclear if increased rates in all-cause SAs were driven by diseases associated with PM exposure. To better understand confounders further information is required, especially pertaining to staff smoking status and co-morbidities.

4.4. Possible solutions to reduce subway PM

While we could not conclude whether exposure to subway PM causes

an increase in SAs in LU staff, high levels of $PM_{2.5}$ are seen throughout the network. Any decrease in $PM_{2.5}$ concentrations will be beneficial to both staff and commuters. This can be achieved by modernising the rolling stock and reducing emissions from activities such as braking (Van Ryswyk et al., 2021). Platform screen doors have been shown to lower platform $PM_{2.5}$ concentrations which can be beneficial for staff and commuters (Jung et al., 2010; Kim et al., 2012). However, platform screen doors increase PM concentrations on the trains (Son et al., 2014). Both approaches should be viewed as long-term changes as they are costly and difficult to implement.

In the short-term, targeted approaches can be used to reduce staff exposure. While the benefit of air purification systems on station platforms has not been extensively studied internationally (Kim et al., 2015; Moreno et al., 2017), their role in reducing indoor PM concentrations have been widely demonstrated (Cheek et al., 2021). Such systems could be used to reduce concentrations found in train cabins and staff offices. Cleaning measures have varying degrees of success depending on methods are used and may reduce short-term PM concentrations; more evidence is required to understand their long-term effectiveness (Chen et al., 2017; Van Ryswyk et al., 2021). Targeted operational changes could be used to reduce the individual staff exposure, especially those with pre-existing medical conditions, by decreasing time spent in high concentration.

5. Conclusions

In conclusion, this study found no clear causal evidence that the exposure to subway $PM_{2.5}$ on the LU increases the risk of sickness absence. However, this does not mean that there are no health effects associated with subway PM exposure. While this study consisted of comprehensive and robust measurements, seeing health effects in the human body is a complex process that may have been hindered by the limitations in the SA data; effects may be sub-clinical or too small to detect in this way.

In their 2019 report, COMEAP concluded that further research is required to understand any health effects associated with exposure to subway PM. This remains the case. Toxicological studies may provide insight into mechanisms on a cellular or organism level, and comparisons made to PM from different sources. Future research should include long-term prospective epidemiological studies, which provide a better means of assessing the adverse health effects of exposure to $PM_{2.5}$ and can be used to investigate the health effects of chronic exposure to subway PM.

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CRediT authorship contribution statement

Justie Mak: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Johanna Feary:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Supervision. **André F.S. Amaral:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Supervision. **Emma Marczylo:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Supervision. **Paul Cullinan:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Funding acquisition. **David C. Green:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The authors declare no competing financial interests that could have influenced the work reported in this paper. The funder had no role in the design of the study, the analysis and interpretation of data, and the decision to publish the results.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

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