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Factors affecting occupational black carbon exposure in enclosed railway stations

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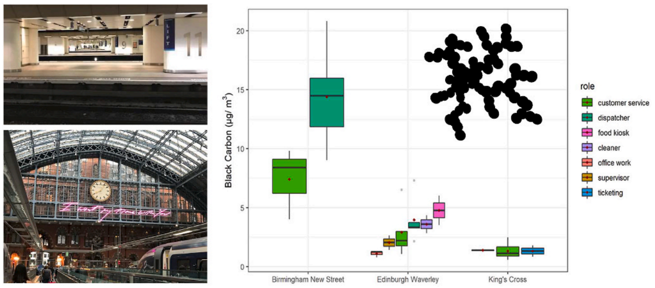
HIGHLIGHTS

- Station design, job role, diesel train frequency are main drivers of occupational BC exposure.
- Occupational BC exposures in enclosed train stations is the highest.
- Dispatchers had the highest work-shift mean exposures.
- Idling diesel trains contribute to elevated occupational exposures to BC.
- Elevated exposures for some job roles indicate the need of mitigation measures.

GRAPHICAL ABSTRACT



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ABSTRACT

Many rail services around the world continue to use diesel as the primary fuel source and enclosed railway stations have been identified as a possible hotspot for exposure to harmful diesel exhaust exposures. Little is known about the occupational exposure to air pollution for railway station workers due to their mobility around the station and variations in station design. A detailed understanding of the concentration of black carbon (BC), a diesel exhaust tracer, inside railway stations and the factors driving occupational exposures is required to minimize occupational exposure. Real-time personal exposure to BC was measured during 60 work-shifts encompassing different roles at three large enclosed railway stations of different design in London, Birmingham and Edinburgh (UK). Sampling was conducted by the train station workers over a period of 27 days between January 2017 to October 2018. Worker shift-mean BC exposures ranged 0.6–20.8 µg m^{-3} but 1-min peak exposures reached 773 µg m^{-3}, with train dispatchers experiencing the highest BC exposures. Station design, job

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role, and frequency of diesel trains were the main drivers of occupational BC exposure. Elevated exposures for some station workers indicate that mitigation measures to reduce their exposure should be implemented to lower the risk of occupational health impacts. These could include improving ventilation and reducing engine emissions.

1. Introduction

Rail is usually considered a green mode of passenger transport, and a more sustainable form of transport than cars and aircraft in terms of its relative impact on climate change (Givoni et al., 2009), as it emits less carbon dioxide (CO_2) per km travelled compared to on-road or air transport (European_Environment_Agency, 2017). It is also an eco-friendly option to increase capital productivity of nations, since investments in rail transport benefit a large number of passengers and transport of goods (Hidalgo and Graftieaux, 2008). Promoting and developing railway systems has therefore become a priority for many governments to achieve sustainable mass transport and reduce CO_2 emissions.

However, rail services also emit pollutants to the atmosphere that are harmful to human health. These include particulate matter of aerodynamic size smaller than 10 μm (PM_{10}) and 2.5 μm ($PM_{2.5}$) originating from mechanical wear from friction of wheels over rails and pantographs with catenary, and during braking events (e.g. wheels, rails and brake pads) (Salma et al., 2007). In addition to the non-exhaust emissions, diesel powered trains emit combustion gases (e.g. CO, CO_2, NO_x, SO_2) and particles that spans the PM_{10}, $PM_{2.5}$ and ultrafine particle size ranges and includes black carbon (BC) (Chong et al., 2015; Givoni et al., 2009; Jaffe et al., 2014; Jeong et al., 2017; Moreno et al., 2015). Whilst other pollutants might have several emission sources into the atmosphere, the primary source of BC in advanced economies is diesel exhaust (Jaffe et al., 2014). Diesel powered trains were estimated to contribute 2.0%, 2.8% and 2.5% respectively, of mobile sources of NO_x, $PM_{2.5}$ and BC in the EU in 2005 (Borken-kleefeld and Ntziachristos, 2012). In addition, many countries and regions of the world still rely on non-electric powered trains, mainly diesel, especially for long-distance journeys (e.g. the European Union has 54% km of their railways electrified (Statista_Research_Department, 2020), the UK has 38% (Edwards, 2019), whereas the USA has only 0.67% (Freeman and Cooper, 2005)).

Exposure to diesel fumes poses a health risk. The International Agency for Research on Cancer reclassified diesel engine exhaust emissions as ‘carcinogenic to humans’ based on sufficient evidence that associated exposure to diesel fumes with an increased risk of lung cancer (Benbrahim-Tallaa et al., 2012; WHO-IARC, 2012). Diesel particles are mostly in the fine fraction and exposure to fine particles has been associated with acute respiratory (Lin et al., 2011; Paunescu et al., 2019; Wang et al., 2022) and cardiovascular problems (Kirrane et al., 2019; Nichols et al., 2013; Song et al., 2022). Studies assessing the impact of diesel engine exhaust on health rely on BC, an indicator of incomplete fuel combustion and a tracer of diesel emissions (Jaffe et al., 2014). Given that enclosed train stations served by diesel engine trains might represent a hotspot for exposure to diesel exhaust emissions, and considering that train station workers spend a large part of their daytime in such environments, it is important to assess occupational exposure of train station workers to diesel engine exhausts, for which BC serves as a good tracer. Moreover, it also important to evaluate the effect of the different design and operational characteristics of the enclosed train stations on occupational exposure so as to recommend measures that could reduce workforce exposure to diesel emissions.

Air quality in railway stations is partially influenced by outdoor pollution originating from traffic and other city-wide and regional sources in the air that is drawn into the stations. However, additional sources of air pollutants inside the station add to this pollution burden including emissions from trains but also from food outlets (Chong et al., 2015; Font et al., 2020) and human activities, such as resuspension of deposited BC particles from walking of passengers (Qian et al., 2014; You and Wan, 2015). These sources can contribute to elevated concentrations of gases and particles in railway stations, particularly those that are largely enclosed (Thornes et al., 2017).

Several studies have assessed the air quality in subway systems, mostly focused on particles, in Europe (e.g. London (Smith et al., 2020), Stockholm (Johansson and Johansson, 2003; Plato et al., 2019), Helsinki (Aarnio et al., 2005), Athens (Mammi-Galani et al., 2017), Rome (Perrino et al., 2015), Barcelona (Martins et al., 2016; Moreno et al., 2015)); East Asia (e.g. Seoul (Kim et al., 2008), Shanghai (Li et al., 2015)), North America (e.g. New York (Vilcassim et al., 2014) Canada (Van Ryswyk et al., 2017)), Latin America (e.g. Sao Paolo (Targino et al., 2021)) and Australia (e.g. Sydney (Mohsen et al., 2018)). Likewise, the majority of air pollution studies in railway environments have only investigated air quality inside the trains or at fixed points in the station (Abbasi et al., 2013). Studies in intercity railway stations show that pollution inside stations is often higher than ambient concentrations due to the presence of diesel trains, including UK stations such as London Paddington (Chong et al., 2015), London King’s Cross (Font et al., 2020), Edinburgh Waverley (Font et al., 2020) and Birmingham New Street (Hickman et al., 2018; Thornes et al., 2020).

The design of railway stations may also play a role in the ventilation of diesel exhaust fumes and other non-exhaust pollutants, and hence in the dispersion or build-up of such pollutants inside the train stations (Font et al., 2020; Thornes et al., 2017). Design factors that might have an effect include: the volume of air over the enclosed platforms available to dilute emission; existence and dimensions of openings that prevent the build-up of pollutants; existence of mechanical ventilation facilitating dispersion of pollutants; and the presence of tunnel-like enclosures over the platforms that might limit the dispersion of the emissions (Hickman et al., 2018). Other relevant factors include whether the concourse is separated from or integrated with the platforms, and the accessibility of passengers to the platforms.

However, what is less well understood is the air pollution that railway station workers breathe during their workday due to their mobility around the station. The majority of occupational health studies conducted thus far have focused mainly on staff actually working on the train as opposed to staff working at the station (Pronk et al., 2009; Verma et al., 2003). Moreover, due to the length of time spent in the stations, rail staff and others working at stations would be the people most affected, rather than passengers and other members of the public. Nonetheless, the high volume of passengers and railway users in stations that host high numbers of trains is also of concern, since these passengers would also be exposed to the same pollution levels, albeit for a limited period of time. Therefore, good occupational and public health are both important considerations in the design and operation of railway stations.

A detailed understanding of the concentration of diesel exhaust pollution inside the railway stations and the factors driving exposures, such as railway station design, is required to understand the relative influence of the railway air pollution sources upon human exposure.

The aim of this study was to understand worker personal exposure to BC, a significant component of diesel emissions, in three enclosed railway stations with distinct designs, through the following objectives:

- Characterising railway station worker personal exposure to diesel emissions during a typical working shift.

- Investigating the dominant variables dictating risk of railway station exposure to diesel emissions, such as time of day, job role, and frequency of diesel trains in station or platform.
- Assessing the effect that railway station design has on railway station worker exposure.

2. Methods

2.1. Railway station description

Three types of station design have been included in this study: (i) Birmingham New Street - a 'through' station with platforms enclosed in tunnel-like enclosures and the concourse located on a separate level above the platforms, (ii) Edinburgh Waverley - a 'through' station with the concourse located in the middle of the platform area, and (iii) London King's Cross - a terminus station where platforms are separated from the concourse. Detailed description of the stations' configurations and ventilation is included hereunder, with diagrams of each station available in the Supporting Information.

2.1.1. Birmingham New Street

Birmingham New Street is a below-ground station, with a large concourse at ground level connected to twelve underground platforms through four sets of staircases and escalators (Fig. S1). The platforms lie in a tunnel-like environment, with approximate dimensions 5 m high, 160 m wide and 240 m in length. This design results in an enclosed platform volume considerably smaller than other enclosed railway stations, such as Edinburgh Waverley or London King's Cross. Trains approach the station from the south-west, north-west and east via three tunnels under the city centre but with lengths of open track between these tunnels and the enclosed platform area. Tracks through the station are electrified, but 45% of the train services run on diesel, with approximately 600 diesel train movements per day (Hickman et al., 2018). The station services 47.9 million passengers per year (ORR, 2022).

2.1.2. Edinburgh Waverley

Edinburgh Waverley station (Fig. S2) is situated in a small valley between the Old Town and the New Town of Edinburgh. This offers the station a degree of shelter from the wind. As it is a 'through' station the primary openings are at either end of the station, which promotes a through draught of air. These primary openings of the station have a west-south-west to east-north-east direction. The main station area has a high, glazed roof. The western end of the station has two additional openings created by two vehicular/pedestrian access ramps. The only vehicles to use this ramp are delivery vehicles for the retail outlets in the station. The station services 23.9 million passengers per year (ORR, 2022) and ~490 (59%) of the 828 trains per day run on diesel (Font et al., 2020).

2.1.3. London King's cross

London King's Cross is a central London terminus. The main station houses platforms 0–8 aligned north to south with a separate adjacent suburban station, positioned at an angle to the main station that houses platforms 9–11 (Fig. S3). These are linked by a semi-circular departure concourse area. Platforms 1–8 in the main station are used for diesel and electric trains and are housed under a double-arched glazed roof. Platform 0, whilst under the main station roof, is partially enclosed with a low roof and separated from the other platforms by a stone wall with openings for pedestrian access, but this doesn't routinely serve diesel trains. Platforms 9–11 are normally served by electric trains only. Since it is a terminus station, the primary external opening is where the trains enter and exit at the north end of the station. This is only a partial opening as the upper arched sections are glazed. Other significant openings are created by the station access doors to the south side of the station. The station services 34.6 million passengers per year (ORR, 2022) and only 18% (~76) of the 420 trains per day run on diesel (Font et al., 2020).

2.2. Sampling campaign

Sixty work shifts were monitored, which comprised of 27 shifts from 9 unique workers at Birmingham New Street, 19 shifts from 16 unique workers at Edinburgh Waverley and 14 shifts from 9 unique workers at London King's Cross. A variety of roles were monitored including cleaners, customer services, train dispatchers, gate-line ticketing, office workers and retail workers.

Monitoring took place over three periods from the 9th to the January 13, 2017 at Birmingham New Street, from the 10th to the September 21, 2018 at Edinburgh Waverley, and from the 22nd to the October 31, 2018 at London King's Cross. The mean shift length monitored was slightly over 6 h, with the majority of workers monitored between 5:00 and 22:00. However, three shifts were monitored at night at London King's Cross (22:00–07:00). The workers' locations within the station depended on their role, but the majority moved throughout the entire station.

2.3. Instruments and data analysis

This study monitors the light absorption characteristics of aerosols by means of the Aethlabs microAeth AE51. The instrument was selected as it provides accurate and high time-resolved measurements. Therefore, formally, measurements in this study are defined as 'equivalent black carbon (eBC)' as they derive mass from an absorption coefficient (Petzold et al., 2013). For simplicity, from here on these equivalent black carbon measurements are referred to as BC.

Following recruitment, each participant was provided with a portable black carbon monitor (Aethlabs microAeth AE51). They were instructed to carry the monitor for their entire shift. The instruments continuously pump air through a short sample tube, the entrance to which was attached as close to the breathing zone of the participant as practical. This was typically at chest height so the inlet would not obstruct their daily work activities. At the end of their monitoring period, the participants completed a short questionnaire relating to their working hours, work activity details and locations in the station. Smoking habits were also recorded (only four participants reported as smokers). Measurements were processed according to predefined data management protocols. These include co-location of each AE51 monitor to a reference aethalometer to calculate a correction factor. The microAeth monitors (AE51) deployed in Birmingham New Street station were co-located against the reference instrument AE33 placed at the central site on platform 10/11 (Hickman et al., 2018). In the case of London King's Cross and Edinburgh Waverley stations, the microAeth monitors (AE51) were co-located against the AE22 at London Marylebone Road belonging to the UK National Black Carbon Network. In Birmingham, the results of the microAeth monitors were corrected directly using the validation equations calculated during the co-location experiments in Birmingham (Supplemental Information). The results of the microAeth monitors used in London and Edinburgh were first corrected using the Kirchstetter filter loading correction factor (Kirchstetter and Novakov, 2007) and secondly, the attenuation-corrected results were corrected using the validation equations calculated during the co-location experiments in London (Supplemental Information).

Flow rates of each monitor were checked for accuracy before each sampling campaign using an Alicat whisper Gas mass flow meter in London and Edinburgh and using a TSI flowmeter in Birmingham. The filter tickets were changed after each shift to avoid any loading effect in the filters (Virkkula et al., 2007).

Measurements were logged as 1-min means and linked to activity and location in the station of the workers provided in time-activity diaries. Pollutant measurements were then tagged according to an activity matrix utilising questionnaire responses provided in the time activity diaries and visual inspection of time series data. Tagged data were used to create summary statistics of exposure for each worker, averaged across their monitoring period. More detailed analysis of measurements during occupational activities were then carried out to identify patterns in their work environment that may have influenced exposure.

Normality of the data was tested using the Shapiro-Wilk normality test. The data was not normally distributed and hence non-parametric test had been used. The unpaired Kruskal-Wallis H test was used to compare differences in worker exposure between stations and according to job roles using shift-averaged exposures. Post hoc tests were run using Dunn's multiple comparison test to identify which specific locations were significantly different. The same tests were run to explore differences between exposures of dispatchers in Birmingham New Street station according to platforms. Data analysis was conducted in R (Version 1.4.1106).

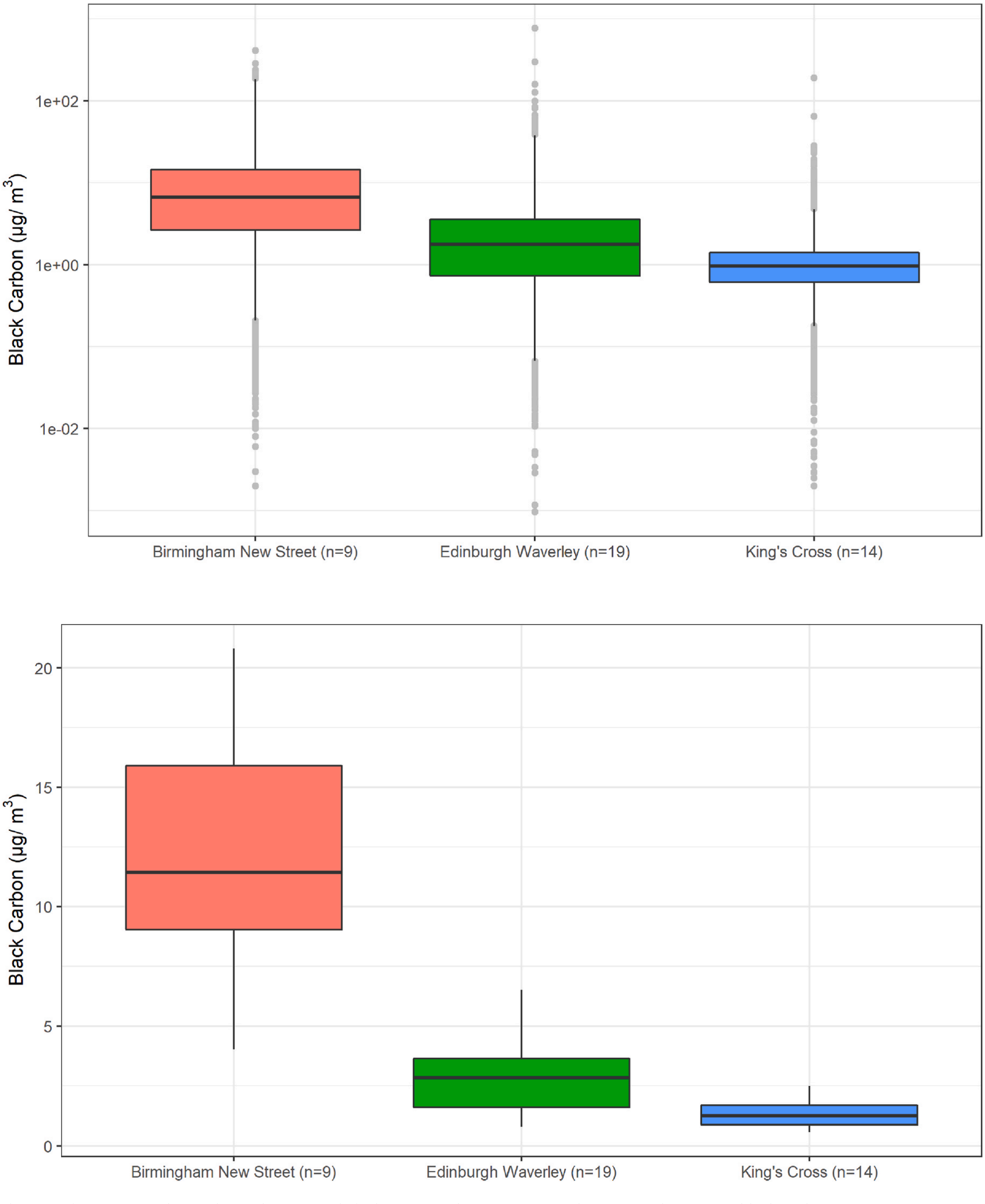

Fig. 1. Distribution of 1-min (top, log-scale) and average shift (bottom) railway station worker personal exposure black carbon concentrations measured in each station. The axes in Fig. 1(top) exclude the outlier values of >80 μg m^{-3}. For the same figure with all outliers shown see Supplementary Information Fig. S4. The n values indicate the number of worker shifts monitored at each station. The boxplot shows the 25 and 75 percentiles, the median (bold horizontal line), the vertical lines signals the upper and lower fences, which are calculated as 75ile +1.5*IQR (interquartile range) and 25ile – 1.5*IQR, respectively. The outliers are shown in grey.

3. Results and discussion

3.1. Worker exposure

Workers at Birmingham New Street station experienced the highest exposures on average (11.9 ± 16.6 μg m^{-3}, standard deviation in 1-min values), followed by workers at Edinburgh Waverley station (3.3 ± 11.5 μg m^{-3}) with workers at London King's Cross station having the lowest exposures on average (1.3 ± 3.2 μg m^{-3}) (Fig. 1, Table 1). The exposures to BC in each station were statistically significantly different ($p < 0.05$). Monitored worker exposure at Birmingham New Street was on average 3.6 times larger than workers' exposures at Edinburgh Waverley, and 9.1 times larger than workers' exposure at London King's Cross. These concentrations are consistent with results from a 2020 survey (Ison, 2021a) conducted in Birmingham New Street, Glasgow Queens Street and Crewe that reported concentrations in the range 1–11 μg m^{-3}, measured as 8-h time-weighted average (TWA) elemental carbon (EC) collected with a personal sampling pump and approved personal sampling cyclone (Ison, 2021b).

The lowest concentrations measured for workers at London King's Cross was very likely due to the lower number of diesel trains at this station (~76 diesel trains per day compared with ~490 and ~600 per day at Edinburgh Waverley and Birmingham New Street, respectively) and because the concourse where workers spend a large proportion of their time at this station is separate from the platforms. The concentrations of BC experienced by workers at Edinburgh Waverley station are higher than those measured at London King's Cross station but lower than those measured at Birmingham New Street station. Although Edinburgh Waverley station serves nearly the same number of diesel trains as Birmingham New Street per day (490 vs 600), its larger interior volume and larger entrances/exits facilitate more rapid dilution and dispersion by natural ventilation of diesel exhaust emitted by diesel train engines compared with Birmingham New Street, which is an enclosed station that requires mechanical ventilation to promote sufficient dispersion of the diesel engine emissions (Clegg et al., 2022). This is discussed in detail below (Section 3.2.1. Railway station design).

Table 1
Summary statistics of 1-min railway station worker exposure to black carbon (μg m^{-3}) by role. Standard deviation (sd) is the variation in the workers' exposure at 1-min resolution. N = number of shifts monitored at Birmingham New Street (BNS), Edinburgh Waverley (EDW) and London King's Cross (KGX) stations.

Role	Station (N)	BC mean ± sd (range)	BC median	BC geometric mean	BC geometric standard deviation
Dispatcher	BNS (18)	13.4 ± 17.0 (0.003–239)	7.8	7.1	3.4
	EDW (5)	4.3 ± 19.0 (0.001–773)	2.3	1.9	3.7
Customer service	BNS (9)	8.2 ± 14.0 (0.002–412)	3.7	3.7	3.8
	EDW (5)	3.1 ± 9.7 (0.003–299)	1.2	1.0	4.7
	KGX (11)	1.3 ± 3.4 (0.002–191)	1.0	0.9	2.4
Supervisor	EDW (2)	2.3 ± 1.8 (0.032–19)	2.0	1.9	1.9
	KGX (1)	1.4 ± 0.7 (0.007–4.8)	1.2	1.2	1.9
Food kiosk worker	EDW (2)	4.8 ± 2.8 (0.197–18)	4.4	4.0	1.9
Cleaner	EDW (2)	3.6 ± 4.1 (0.005–45)	2.6	2.1	3.3
Office worker	EDW (3)	1.1 ± 0.7 (0.187–9.3)	0.9	0.9	1.7
Gateline ticketing	KGX (2)	1.4 ± 1.8 (0.057–17)	0.8	0.9	2.4
All data by station	BNS (27)	11.9 ± 16.6 (0.002–412)	6.7	5.9	3.6
	EDW (19)	3.3 ± 11.5 (0.001–773)	1.8	1.5	3.6
	KGX (14)	1.3 ± 3.2 (0.002–191)	1.0	0.9	2.4

The age of the rolling stock may be another factor affecting worker exposures at the three locations. A greater proportion of the trains serving London and Birmingham stations are newer than those in Edinburgh, i.e. rolling stock age range in Birmingham is 12.5–18.4 years old in 2016–17, whilst the age of the trains in London is 11.3–25.5 years old and 11.8–38.5 years old in Edinburgh in 2017–18 (ORR, 2022). Newer diesel trains may incorporate exhaust after-treatment technologies which will lower the diesel emissions (Norris et al., 2019). Therefore, the larger numbers of older trains at Edinburgh might have been another contributing factor to the differences observed between the stations (Hickman, 2018).

Another factor that might have affected the elevated concentrations observed in Birmingham compared to London or Edinburgh stations is the function of the station. The train stations in London and Edinburgh are terminus, whereas the train station in Birmingham is a major interchange station, with a higher frequency of idling trains than the other two. Idling diesel locomotives engines also have high emission rates (Grennan-Heaven and Gibbs, 2020; Kim et al., 2020). Kim et al. (2020) measured concentrations emitted by several diesel locomotive engines during idling and reported elevated concentrations of particulate matter (43.4 ± 6.84 mg/m^3), nitrogen oxides (147 ± 19.46 ppm), carbon monoxide (94 ± 44.23 ppm), and hydrocarbons (4.3 ± 0.02 ppm). A recent fleet-wide assessment of emissions factors on diesel locomotive engines used in UK highlighted the considerable emission of trains during idling compared to other engine notches, both for NOx (34 g/kWh vs 4–11 g/kWh) and PM (1.7 g/kWh vs 0.1–0.3 g/kWh) (Grennan-Heaven and Gibbs, 2020).

Weather conditions might affect the concentrations experienced by stations workers. During days of high pressure, similar to those experienced whilst sampling was conducted in London (Table S1), the atmospheric stability could potentially lead to higher than normal exposures inside the station due to stagnant air. In contrast, lower atmospheric pressure was observed during the sampling periods in Birmingham and Edinburgh, accompanied by higher than typical wind speeds. These synoptic conditions might have facilitated the dispersion of pollutants away from the train stations and could potentially have lowered the exposure of workers at these stations. On the other hand, the sampling occurred in months with cooler temperatures: January, September, and October. Therefore, seasonal differences could not be evaluated.

The large standard deviations in comparison to the mean indicate intermittent high pollution exposures experienced by the workers (Fig. 2). The highest 1-min exposure experienced at Edinburgh Waverley was 773 μg m^{-3} when a worker was dispatching trains. Similarly, the highest 1-min exposure experienced at London King's Cross was 191 μg m^{-3} by a customer services worker. In Birmingham New Street, in spite of the higher average BC exposure being experienced by dispatchers, the highest 1-min exposure was recorded by a customer service worker (412 μg m^{-3}). This suggests that despite the differences in mean exposures, in all three stations workers could be exposed to very high concentrations of pollution, albeit for very short durations.

Shift mean BC worker exposure at London King's Cross was lower than other transportation occupational exposures measured in previous studies (Barratt, 2018). On the other hand, the BC exposure of dispatchers at Birmingham New Street was similar to those experienced by truck drivers (measured as EC) (Baccarelli et al., 2014) and taxi drivers (Du et al., 2011b) in Beijing. Customer services workers at Birmingham experienced similar exposures to those reported for waste truck workers in South Korea (Lee et al., 2015b). The BC exposure of kiosk food workers, cleaners, customer services and dispatchers at Edinburgh Waverley was similar to that experienced by taxi drivers in New York City (Gany et al., 2017b).

The exposure of dispatchers at Birmingham New Street is within the

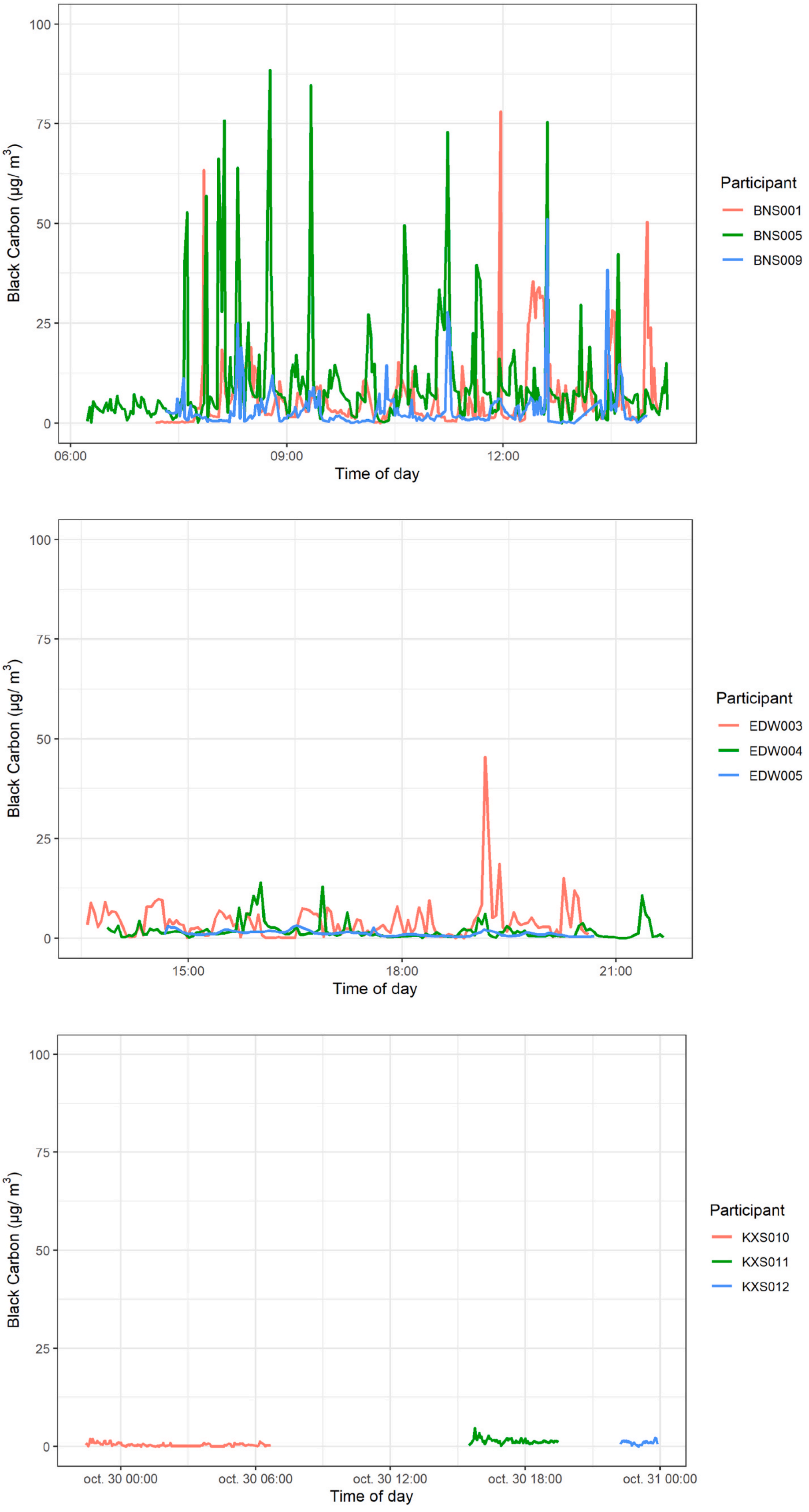

Fig. 2. Example of the variability in 1-min average black carbon exposures experienced by railway station workers at Birmingham New Street Station (top) on January 13, 2017 (BNS001 and BNS005 dispatcher, BNS009 customer services), Edinburgh Waverley Station (middle) on September 10, 2018 (EDW003 cleaner, EDW004 customer services and EDW005 office worker) and London King's Cross (bottom) on October 30, 2018 (KXS011 supervisor, KXS010 and KXS012 customer services).

range of concentrations measured in the majority (80%) of platforms and stations at various lines in the New York subway system, with means ranging 8–23 μg m^{-3}. On the other hand, the exposures of dispatchers at Edinburgh Waverley are in the range of the few platforms/station (20%) measuring the lowest concentrations (1.7–7.5 μg m^{-3}) (Vilcassim et al., 2014). Whilst only comparisons to subway stations are possible because of the lack of studies on inter-city train stations, caution is required because aethalometer measurements of BC in subway settings may suffer interference from light-absorbing metals, such as iron oxides (Cai et al., 2013, 2014; Fialho et al., 2006).

Occupational exposure to BC of train station workers is higher than that experienced by passengers at the train stations, especially for station workers in Birmingham, as the passenger are transient in the station, whilst the workers stay at the station for the duration of the job shift. Whilst BC concentrations measured by dispatchers at Birmingham New Street are similar to those measured inside cars in Barcelona (de Nazelle et al., 2012), and subway passengers in Shanghai (Li et al., 2015), taxi drivers in Beijing (Du et al., 2011a) and waste truck workers in Korea (Lee et al., 2015a). On the other hand, occupational exposures in Birmingham train station are higher than those measured in other car exposure studies in Europe (Cepeda et al., 2017; Karanasiou et al., 2014). Dispatchers at Edinburgh Waverley are exposed to BC concentrations similar to those measured by pedestrians in main streets (de Nazelle et al., 2012; Moreno et al., 2015); bus and subway passengers in London (Rivas et al., 2017), Barcelona (Moreno et al., 2015) and Flanders (Dons et al., 2012). They are also similar to exposures experienced by pedestrians and cyclists in Shanghai (Li et al., 2015), and by car passengers in London (Rivas et al., 2017) and Flanders (Dons et al., 2012). Likewise, exposure of dispatchers at Edinburgh Waverley are similar to those experienced by train passengers in Birmingham (Delgado-Saborit, 2012), Toronto (Jeong et al., 2017) and Boston (Hill and Gooch, 2010). Occupation exposures in Edinburgh Waverley station were also similar to those experienced by taxi drivers in New York, Lebanon, Paris and Barcelona (Gany et al., 2017a; Hachem et al., 2020, 2021; Moreno et al., 2019). Shift exposures at Edinburgh Waverly were also similar to exposures measured by professional drivers in London (Lim et al., 2021). On the other hand, occupation exposure of train station workers in the three locations studied are considerably lower than exposures experienced by bus drivers in Nairobi (Kenya) (Ngo et al., 2015). However, caution should again be exercised in comparing aethalometer measurements in locations dominated by different sources, i.e. subway vs diesel exhaust. This is due to the sensitivity of this method to other light absorbing aerosols, such as iron oxides (Cai et al., 2013, 2014; Fialho et al., 2006).

The elevated exposures measured for Birmingham New Street railway station workers indicate that mitigation measures to reduce exposure to air pollution at the station should be implemented. In addition, despite lower exposures in general for workers at Edinburgh Waverley and London Kings Cross stations, the highest shift exposure measured across both stations was 7.3 ± 10.1 μg m^{-3} for a train dispatcher at Edinburgh Waverley, indicating that mitigation of high exposures for certain station workers should be investigated.

Key mitigation methods that are currently being adopted at Birmingham New Street station are to reduce idling time by changing driver behaviours and installing auto shutdown of vehicles; and to reduce exposure by increasing the rotation of staff between platforms. In addition, over one hundred NO_2/NO_x sensors have been installed to assist in driving the ventilation system (Thornes et al., 2020).

Since these studies were undertaken, the proportion of electric trains serving London Kings Cross and Edinburgh Waverley has increased considerably and plans to reduce the proportion of diesel trains at Birmingham New Street have also been announced.

3.2. Factors affecting worker exposure

3.2.1. Railway station design

Fig. 1 and Table 1 shows that worker exposure varies considerably between train stations. At London King's Cross the lowest exposures occurred at the concourse but at Birmingham New Street, the highest exposures were for workers at the concourse (i.e. customer services) and platforms (i.e. dispatchers).

The architectural design of the railway stations plays a role. Birmingham New Street station is an enclosed station, which facilitates the build-up of train emissions due to its small airshed volume, and reduced ventilation in platforms 8 to 12 due to the positioning of the East opening on a 90° angle (Fig. S1). In addition, the build-up of pollutants at the platform level appears to be dispersing into the concourse level and affecting the exposures of workers at the concourse level, such as customer services. In addition, in enclosed train stations the piston effect should be taken into account. In the one hand, the piston effect will promote ventilation, but on the other hand, it would increase airborne concentrations of aerosol pollutants deposited in the ground by resuspension of the tail wind (Moreno et al., 2014; Pan et al., 2013; Targino et al., 2021).

On the other hand, BC exposures for both dispatchers and customer services workers at Edinburgh Waverley are lower than those measured at Birmingham New Street. Although the concourse at Edinburgh Waverley is embedded in the middle of the station at the same level as the platforms, the airshed of the station is much larger than that at Birmingham New Street since the roof is at least 10 m high. Furthermore, its openings at each end of the station are aligned with the predominant wind direction from the south-west, allowing for more efficient dispersion of pollutants (Fig. S2).

Workers at London King's Cross experience the lowest exposure among the three studied railway stations. Whilst the platforms are housed in a building similar to that at Edinburgh Waverley the concourse is separated from the platforms by a partition wall with an opening only for platform access (Fig. S3).

Our results are consistent with those reported in bus stations in Hong Kong, where enclosed bus stations experienced higher BC concentrations than those with an open design (Yang et al., 2015).

3.2.2. Exposure by worker role

Dispatchers at Birmingham New Street station had the highest workshift mean exposures (13.4 ± 17 μg m^{-3}) (Fig. 3, Table 1). At Edinburgh Waverley, dispatchers also had high exposures (4.3 ± 19 μg m^{-3}), second only to those measured by food kiosk workers (4.8 ± 2.8 μg m^{-3}), who were cooking and preparing food as part of their job role. The substantially high standard deviation but low mean concentrations reveals that exposures at platforms were often low, when there was an absence of trains, but were subject to significantly higher peaks for a short period of time when trains were at the platforms. Most likely, the elevated exposures experienced by dispatchers is associated with their role being in close proximity to idling and passing diesel trains when on the platforms. In addition, dispatchers at Birmingham New Street might record the highest exposures due to the more enclosed nature of this train station (Hickman et al., 2018).

Customer service workers at Birmingham New Street, located in the concourse area, had the second highest exposure (8.2 ± 14 μg m^{-3}). This suggests that BC emissions produced by trains on the underground platforms are transported upwards via the staircases and escalators to the concourse. Hickman et al. (2018) reported similar results for NO_2 concentrations measured with passive samplers (stationary monitoring), showing concentrations at the concourse level similar to those measured at the platform level. Customer service workers at Edinburgh Waverley

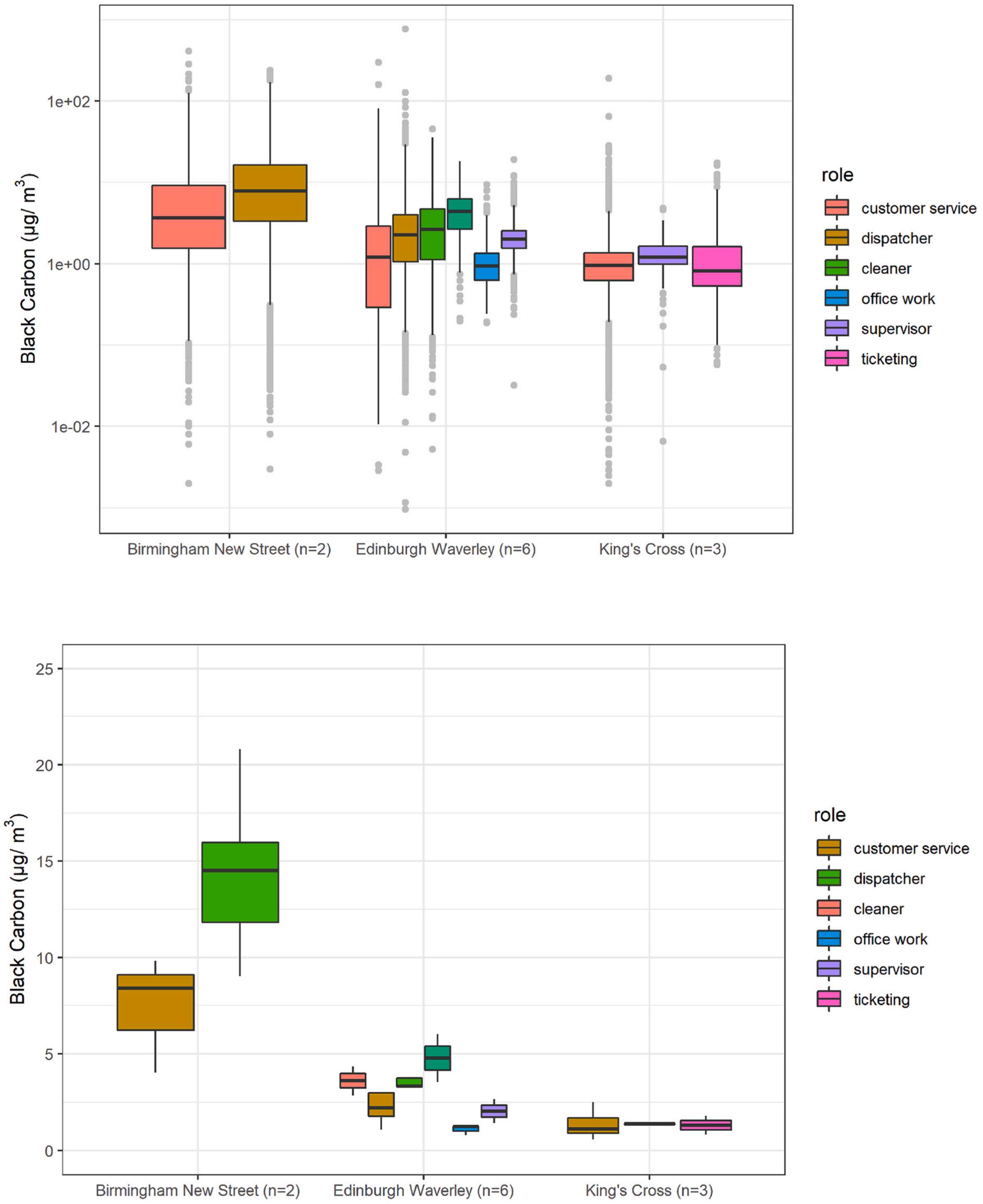

Fig. 3. Distributions of 1-min (top, log-scale) and average shift (bottom) BC exposures based on railway station worker role in Birmingham New Street (left), Edinburgh Waverley (centre) and London King's Cross (right) stations. The number of individual shifts contributing to each box plot is given by the N value in Table 1. The axes in Fig. 3(top) exclude the outlier values of >80 µg m^{-3}. For the same figure with all outliers shown see Supplementary Information Fig. S5. The boxplot shows the 25 and 75 percentiles, the median (bold horizontal line), the vertical lines signals the upper and lower fences, which are calculated as 75ile +1.5*IQR (interquartile range) and 25ile – 1.5*IQR, respectively. The outliers are shown in grey.

had exposures (3.1 ± 9.7 µg m^{-3}) similar to those experienced by dispatchers at that station (4.3 ± 19 µg m^{-3}), most likely due to their work near train platforms. Customer services staff at London King's Cross experienced the lowest BC concentrations observed for that role (1.3 ± 3.4 µg m^{-3}).

At Edinburgh Waverley station, food kiosk workers had the highest mean exposure (4.8 ± 2.8 µg m^{-3}). In contrast to dispatchers, these workers were exposed to less variation in BC concentrations, suggesting that moderately high concentrations persisted for the entire shift. The elevated concentrations for this role were most probably due to the kiosk being positioned in the middle of the concourse where BC concentrations are more homogeneously mixed and that the kiosk is likely to create its own localised source of BC from cooking activities.

Cleaners at Edinburgh Waverley station, whose work is near train platforms, also show elevated exposures (3.6 ± 4.1 μg m^{-3}), similar to those reported by dispatchers and customer services in that station. In contrast, BC exposures of office workers at Edinburgh Waverley station were the lowest measured in any of the three train stations (1.1 ± 0.7 μg m^{-3}).

At London King's Cross station, similar low mean exposures were experienced by staff in the gateline ticketing (1.4 ± 1.8 μg m^{-3}), customer services (1.3 ± 3.4 μg m^{-3}) and supervisor (2.3 ± 1.8 μg m^{-3}) roles. Overall, average worker exposure at London King's Cross station (1.3 ± 3.2 μg m^{-3}) was similar to that of office workers at Edinburgh Waverley station. This result emphasises the absence of BC sources on the concourse where the workers were located at London King's Cross. However, no dispatchers were monitored at London King's Cross due to a lack of volunteers and this role would likely be subject to higher BC exposures due to proximity of work near platforms, as has been observed in the other two stations.

The Kruskal-Wallis test showed a significant difference between roles ($p < 0.01$, df = 5). The post hoc Dunn's pairwise test found a significant difference ($p < 0.05$) between customer services workers and food kiosk exposures; between office workers and cleaners, customer services, dispatchers and food kiosk and between supervisors and food kiosk and office workers in Edinburgh Waverley station. In Birmingham New Street station dispatchers and customers services exposures were significantly different ($p < 0.05$). No differences were observed between gateline ticketing, supervisor and customer services in King's Cross London station.

These results are consistent with occupational exposures reported in three British train stations measured as 8-h TWA of EC (Ison, 2021a). Train dispatchers and personnel working in the platforms (e.g. fitters) experienced the highest exposures, followed by security and gate liners, with ticket sales (away from the platforms) and mobility personnel recording the lowest occupational exposures (Ison, 2021a).

3.2.3. Diurnal variation of exposures

BC exposures at Birmingham New Street station are strongly related to the presence of diesel trains in the train station, with high exposure (between 10 and 15 μg m^{-3}) from 6:00 until 22:00 concurrent with traffic of diesel trains through the station (Fig. 4). A similar trend is observed in Edinburgh Waverley, albeit with lower concentrations (between 2.5 and 7 μg m^{-3}). On the other hand, the diurnal variability of worker's exposures at London King's Cross cannot be explained by the presence of diesel trains only. This is likely due to the differing mobilities and locations of exposures of the workers according to their roles (such as being in an office, or on the concourse) and the fact that no dispatchers, who normally work at the platform, could be measured at London King's Cross.

The diurnal variability of BC exposures in Edinburgh Waverley and London King's Cross stations were not as large as in Birmingham New Street station (Fig. 4), with hourly exposures less than 5 μg m^{-3} for most of the hours at Edinburgh Waverley; and exposures 1–2 μg m^{-3} at London King's Cross. As in Birmingham New Street station, there were significantly lower exposures for those working on early morning and night shifts in Edinburgh Waverley station than those working between 6:00 and 22:00 (e.g. 3.1 vs 1.8 μg m^{-3}).

Further analysis of individual time series reveals the significant variation in BC exposure experienced by railway station workers during a shift and potential explanations for these variations (Fig. 5). Dispatch workers at Birmingham New Street station showed a large frequency of very high peaks of BC exposure during the time that they were at the platforms related to passing and idling trains in their platform and adjacent platforms, followed by periods with lower exposures and fewer peaks whilst in the office or on rest breaks (Fig. 5a), according to the data logged in the time activity diaries. In contrast, the BC exposure of workers at Edinburgh Waverley and London King's Cross stations was relatively low for long periods of the day, but this was punctuated by short intermittent peaks. For a dispatcher at Edinburgh Waverley this was probably due to trains arriving at platforms (Fig. 5b). While lower peaks were observed at London King's Cross (Fig. 5c), intermittent peaks in exposure were still evident. In this instance, the peaks could be due to ambient pollution infiltrating into the station or due to transport of emissions of trains from platforms moving into the concourse carried away by the movement of passengers in and out of the platform area.

Infiltration of outdoor emissions could influence the concentrations measured inside the train stations. This influence would have a diurnal pattern similar to that of the outdoor emission sources, e.g. exhaust from diesel buses (Plato et al., 2019). However, the experiment setup did not allow simultaneous quantification of concentrations in both outdoor and indoor environments. In addition, instruments from reference stations from the national and local monitoring network are not located in the vicinity of the stations. Hence, we could not determine the level of the infiltration of outside diesel emissions into the station and assess its contribution to the occupational exposures. On the other hand, it is likely that this would be minimal compared to the contribution from the emissions from diesel trains. Likewise, the influence of outdoor emission sources would be similar for all workers in the station independent of the activity that they were undertaking.

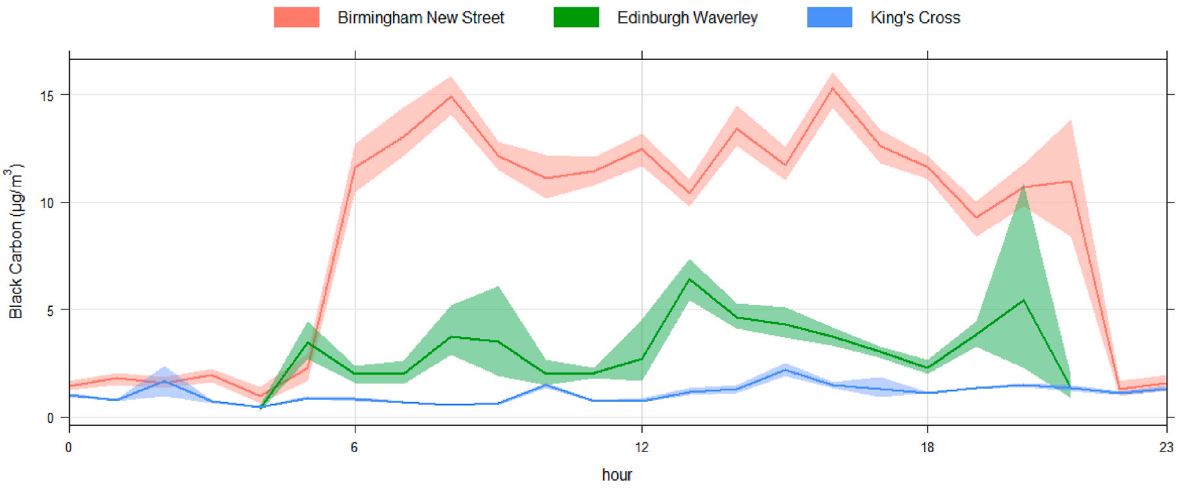

Fig. 4. Mean (1-h) diurnal variation of railway station workers' BC exposures for all workers at each station.

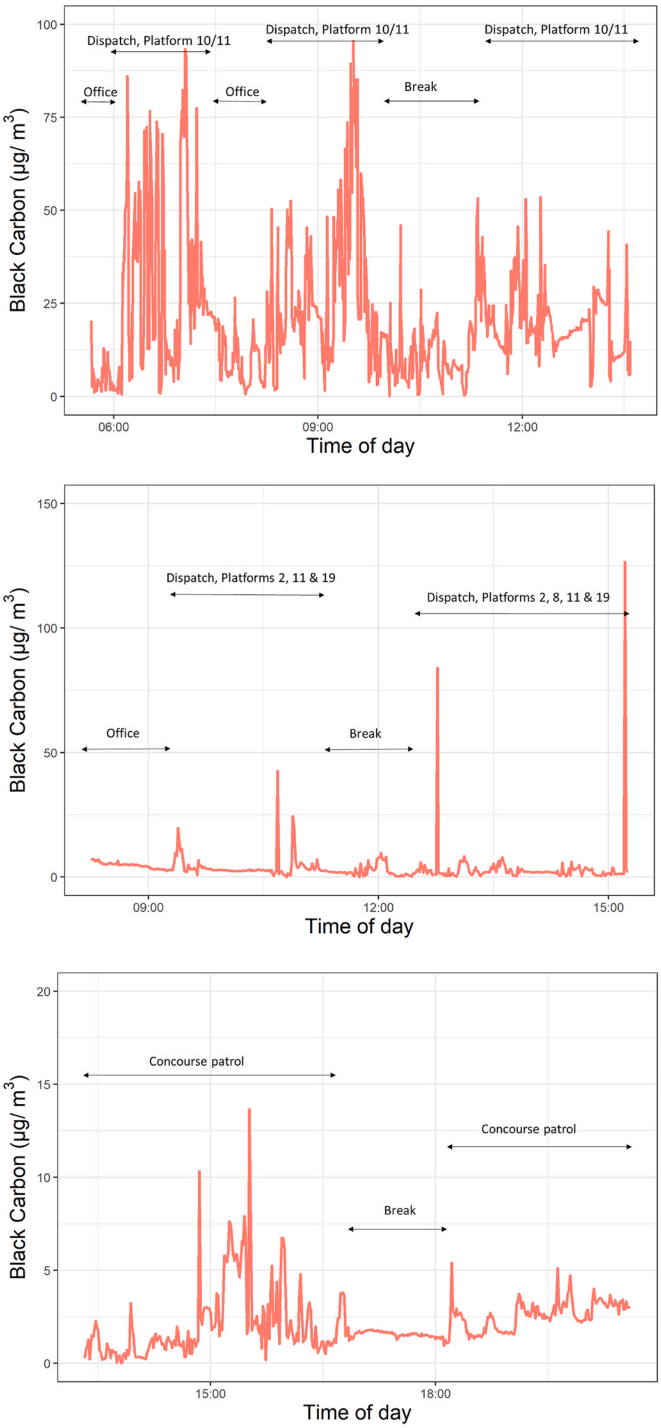

Fig. 5. Time series of 1-min black carbon exposure illustrating variation in exposure between activities at Birmingham New Street station for dispatcher BNS006 shift on 10/01/2017 (top), at Edinburgh Waverley station for dispatcher EDW008 on 11/09/2018 (middle) and at London King's Cross station for customer services KXS001 shift on 22/10/2018 (bottom).

3.2.4. *Variability of exposures by platform*

Fig. 6 presents the average exposure of dispatchers at Birmingham New Street station according to the platform number they serviced. Dispatchers at the island comprising platforms 10/11 (Fig. S1) experienced the highest BC exposure (21.6 ± 18.0 μg m^{-3}). This is consistent with the fact that this platform predominantly serves diesel trains, many of which remain idling for a significant period of time. Furthermore, due to the curved geometry of the platforms on the south side of the station, where platforms 10/11 are located, poor ventilation is likely to occur, resulting in reduced dispersion of pollutants and therefore higher concentrations.

In contrast, dispatchers at the island serving platforms 8/9 experienced the lowest exposures within the dispatcher workers at Birmingham New Street station. This platform predominately serves electric rolling stock and appears to be unaffected by the adjacent platform 10/11 serving mainly diesel trains.

The Kruskal-Wallis test showed a significant difference between platforms ($p < 0.01$, df = 5). The post hoc Dunn's pairwise test found a significant difference ($p < 0.05$) between dispatchers exposures in the island serving platforms 10/11 and dispatchers serving any other islands. Likewise, dispatchers serving platform 8/9 had significantly lower exposures than dispatchers serving platforms 6/7 and 1 ($p < 0.05$).

3.3. *Comparison with fixed monitors and exposure limits*

Fixed monitor measurements of BC were concurrently conducted at the three stations. The methodology to measure BC concentrations at fixed locations in these stations is detailed in Hickman et al. (2018) for Birmingham New Street and Font et al. (2020) and Green et al. (2019) for London King's Cross and Edinburgh Waverley (Font et al., 2020; Green et al., 2019; Hickman, 2018).

Overall, worker exposures to BC were lower than environmental BC concentrations measured at fixed points in Birmingham New Street (22.7 ± 23.2 μg m^{-3}) (Hickman, 2018), Edinburgh Waverley (5.0 ± 5.2 μg m^{-3}) and London King's Cross (5.3 ± 5.9 μg m^{-3}) (Font et al., 2020) train stations. This reflects workers being in lower pollution areas such as in the office or away from the platforms for a substantial proportion of their workday. It should be highlighted that at Edinburgh Waverley the fixed monitor was located close to the Operations Depot and lower concentrations of NO_2 and $PM_{2.5}$ were observed at this location compared to other sites within the station (Green et al., 2019). At London King's Cross the monitor was located on Platforms 0/1 and therefore higher concentrations arising from trains were expected. This explained the slightly higher concentration measured at the monitor in London King's Cross. Personal exposure results show that workers at London King's Cross did not frequent this location and were often in the separated concourse where lower exposures were measured. The Edinburgh Waverley results also suggest that fixed monitors did not reflect the significant variability in exposures experienced by workers. The Birmingham New Street fixed monitor was located in the middle of the island serving platforms 10/11, which is the location with the highest frequency of diesel trains and the lowest ventilation, as it is at considerable distance from the west and east openings.

The comparison between fixed and worker exposure is important as there has been growing evidence that high short-term exposures can have adverse health effects (Behndig et al., 2011; Riediker et al., 2004; Yu et al., 2017). These findings should be considered when identifying locations for recording air pollution concentrations in railway station environments, and in implementing recommendations to reduce pollution exposure, as fixed measurements may potentially overstate worker exposure and may not accurately represent the variability in exposures experienced by workers. Note that the research team had little choice in the selection of locations for certain monitors due to site constraints.

There is currently no occupational exposure limit for BC. However, the EU has recently agreed to implement a 50 μg m^{-3} exposure limit from diesel engine exhaust emissions (measured as elemental carbon) averaged over an 8-h shift (EU, 2019). There is no applicable ambient (i.e., non-occupational) standard for BC. However, as BC is a component of fine particulate matter ($PM_{2.5}$), the closest applicable ambient standard is the EU limit value (EU, 2008) and the WHO ambient air quality guideline (WHO, 2021) for $PM_{2.5}$, set at 25 μg m^{-3} and 15 μg m^{-3} averaged over 24 h, respectively. The shift-average exposures to BC for the volunteers in this study were substantially lower than both of the

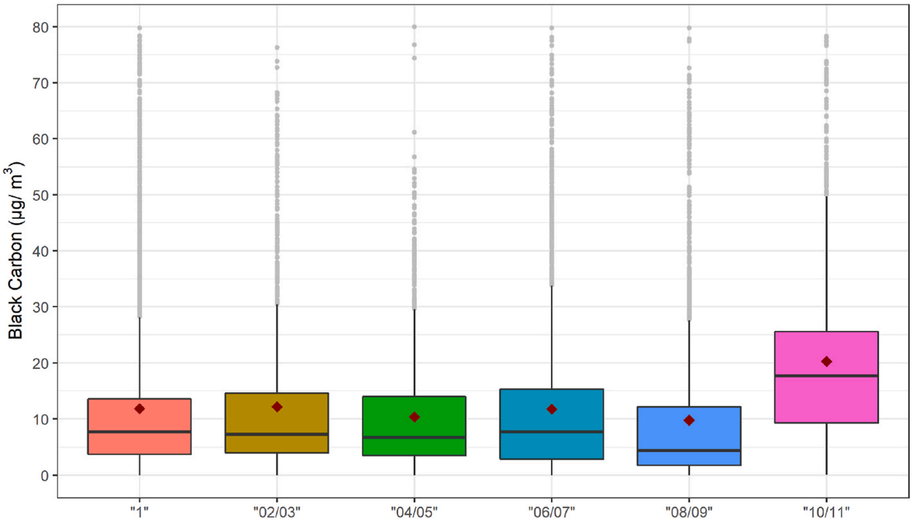

Fig. 6. Distribution of 1-min BC exposures based on platform location of dispatchers in Birmingham New Street (a plan of the station is given in Supplementary Information Figure S). The axes exclude the outlier values of >80 μg m^{-3}. For the same figure with all outliers shown see Supplementary Information Fig. S6. The boxplot shows the 25 and 75 percentiles, the mean (red diamond) and median (bold horizontal line), the vertical lines signals the upper and lower fences, which are calculated as 75ile +1.5*IQR (interquartile range) and 25ile – 1.5*IQR, respectively. The outliers are shown in grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

above two concentration values.

While exposures were lower than these values it should be noted that some studies (Maynard et al., 2007; Tobias et al., 2014) have found significant health effects for small increases in BC (~1.5 μg m^{-3}). In addition, these workers are exposed to other pollutants (Font et al., 2020; Thornes et al., 2017), such as NO_2 and $PM_{2.5,}$ which can also elicit health effects (Ab Manan et al., 2018; Bazyar et al., 2019; Costa et al., 2014; Mills et al., 2016; Pope and Dockery, 2006).

In summary, this study utilised high time resolution portable black carbon exposure monitors to characterise exposures of volunteer workers in railway stations to diesel exhaust emissions across a range of occupational environments in three major UK railway stations of different design. Black carbon is an indicator of incomplete fuel combustion, the primary source of which in this occupational environment is train diesel exhaust.

Worker exposures to BC were higher ($p < 0.05$) on average in Birmingham New Street station (11.9 ± 16.6 μg m^{-3}, standard deviation in 1-min values, $n = 27$ shifts monitored) than in Edinburgh Waverley station (3.3 ± 11.5 μg m^{-3}, $n = 19$), which were significantly higher than in London King's Cross station (1.3 ± 3.2 μg m^{-3}, $n = 14$). The latter station operates substantially fewer diesel train services. Station design is also important: emissions build-up in the underground enclosed platforms at Birmingham New Street and subsequently disperse up to the ground-level concourse; Edinburgh Waverley Station has a larger volume and through dispersion; at London King's Cross there is some physical separation between concourse and platform areas. Workers were more highly exposed at train platforms compared to other parts of the station. The lowest concentrations were found in office environments, which attenuate some diesel emission infiltration. Exposures on shifts between 6:00 and 22:00 were significantly higher than early morning or night shifts.

The shift-average exposures to black carbon for the volunteers in this study were substantially lower than a recently agreed exposure limit (50 μg m^{-3}) for exposure to diesel-engine exhaust emissions. However, while a high proportion of a worker's day exhibited low black carbon exposure, at times 1-min exposures reached several hundred μg m^{-3}. Comparison with time-activity diary information indicate it is likely that this high exposure was due to workers standing in close vicinity to diesel train exhaust emissions. Black carbon concentrations have been shown to decrease exponentially away from the source, therefore moving even short distances away from an exhaust or away upwind from the engine could make a major difference to exposure.

3.4. *Initiatives to improve air quality within enclosed stations*

Since measurements were conducted at Birmingham New Street train station, focus groups were established leading to many initiatives to improve the air quality within the station. These initiatives are the basis of the Air Quality Strategic Framework, a new Environmental Sustainability Strategy and a Ten point Air Quality Action Plan launched by Network Rail in 2020. All of them aimed at improving air quality across the UK rail network. The Action Plan sets-up a new Air Quality Standard to manage and improve air quality in the stations and depots within the network, establishes air quality monitoring plans implemented regionally and has created and delivered air quality briefing packs to the stations and regions, among other measures. The main interventions implemented are aimed at reducing the emission of air pollutants from trains by encouraging more electric/hybrid trains and reducing train idling (Thornes et al., 2020). These measures include upgrading software to facilitate the auto-shutdown on class 220/221s locomotives, establishing a process for platform supervisors to monitor and record excess idling, especially to encourage train drivers to switch off idling diesel engines (Thornes et al., 2020) and to deliver informative talks to promote behaviour change. Focus groups are examining the process of coupling/decoupling trains to avoid excessive acceleration in hot spots around the station, and to agree mitigations and innovations to improve air quality across the rail network. Other measures aimed at improving ventilation by installing nitrogen monoxide/dioxide sensors to drive the ventilation system combined with sonic wind sensors to define the directionality of the operation of the fans (Thornes et al., 2020). These improvements on the ventilation systems have reduced NO_2 concentrations by approximately 30% (Clegg et al., 2022). In addition, a Network Rail health-screening programme has been implemented targeting all dispatch staff. Finally, the improvements made at New Street Station are being expanded to other enclosed train stations at risk of air pollution. To this effect, Network Rail has set up Air Quality Focus Group workshops with relevant stakeholders to ensure consistency in monitoring and to share data and best practices to reduce air pollution in the train stations across the network.

These initiatives might be useful examples to guide through the proposal of mitigation measures in other enclosed train stations where high levels of air pollution are measured.

4. Conclusions

This study characterised occupational exposure to BC encompassing different roles at three large enclosed railway stations of different design in London, Birmingham and Edinburgh (UK). Results show that train dispatchers experience the highest BC exposures. Station design, job role, and frequency of diesel trains were the main drivers of occupational BC exposure. Elevated exposures for some train station workers indicate that mitigation measures to reduce their exposure should be implemented to lower the risk of occupational health impacts.

The evidence provided in the present study can help architects and civil engineers to design railway stations that prevent the accumulation of harmful pollutants in the station. For existing enclosed railway stations, whilst changing the station design is costly, technical solutions that prevent or at least reduce diesel emissions of trains within the station and that facilitate ventilation of emissions in the station, alongside replacing old diesel train stock with electric trains is likely to significantly reduce exposures to railway station workers. Overall, measures aimed at improving the air quality within the station, and reducing occupational exposures will also be beneficial for train passengers.

CRediT authorship contribution statement

Juana Maria Delgado-Saborit: Conceptualization, Methodology, Validation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Shanon Lim:** Validation, Investigation, Data curation, Writing – review & editing. **Alice Hickman:** Validation, Investigation, Data curation, Writing – review & editing. **Chris Baker:** Conceptualization, Methodology, Writing – review & editing, Project administration, (Birmingham subset), Funding acquisition, (Birmingham subset). **Benjamin Barratt:** Conceptualization, Methodology, Writing – review & editing. **Xiaoming Cai:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition, (Birmingham subset). **Anna Font:** Conceptualization, Methodology, Data curation, Writing – review & editing. **Mathew R. Heal:** Conceptualization, Methodology, Writing – review & editing. **Chun Lin:** Validation, Investigation, Data curation, Writing – review & editing. **John E. Thornes:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition, (Birmingham subset). **Michael Woods:** Conceptualization, Supervision, Writing – review & editing. **David Green:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, (Edinburgh and London subset), Funding acquisition, (Edinburgh and London subset).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2022.119301.

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