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Characterising professional drivers' exposure to traffic-related air pollution: Evidence for reduction strategies from in-vehicle personal exposure monitoring

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ABSTRACT

Professional drivers working in congested urban areas are required to work near harmful traffic related pollutants for extended periods, representing a significant, but understudied occupational risk. This study collected personal black carbon (BC) exposures for 141 drivers across seven sectors in London. The aim of the study was to assess the magnitude and the primary determinants of their exposure, leading to the formulation of targeted exposure reduction strategies for the occupation. Each participant's personal BC exposures were continuously measured using real-time monitors for 96 h, incorporating four shifts per participant. '*At work*' BC exposures (3.1 ± 3.5 μg/m^3) were 2.6 times higher compared to when *'not at work'* (1.2 ± 0.7 μg/m^3). Workers spent 19% of their time *'at work driving'*, however this activity contributed 36% of total BC exposure, highlighting the disproportionate effect driving had on their daily exposure. Taxi drivers experienced the highest BC exposures due to the time they spent working in congested central London, while emergency services had the lowest. Spikes in exposure were observed while driving and were at times greater than 100 μg/m^3. The most significant determinants of drivers' exposures were driving in tunnels, congestion, location, day of week and time of shift. Driving with closed windows significantly reduced exposures and is a simple behaviour change drivers could implement. Our results highlight strategies by which employers and local policy makers can reduce professional drivers' exposure to traffic-related air pollution.

1. Introduction

Continuous measurements of individuals' personal exposure to air pollution is considered the 'gold standard' for exposure assessment (Health Effects Institute, 2010), as personal measurements more accurately represent the complexity and variability in daily exposures experienced by individuals compared to other assessment methods (Kaur et al., 2007). Personal exposure studies, which utilise portable monitors to measure diurnal patterns of people's exposure, have consistently shown that the commuting period of an individual's day results in the highest air pollution exposure (Lim, Salmond, et al., 2015). With travelling in motor vehicles often resulting in the highest exposures compared to other modes of transport (de Nazelle et al., 2017).

While the general population may typically commute one to two hours each day, professional drivers are often required to be in this environment for their entire shift (typically between 8 and 16 h). This is a concern as higher concentrations of traffic derived pollutants have been found to be associated with a range of negative health impacts, including increased cardiopulmonary mortality (Atkinson et al., 2016), hospitalisations for cardiac and respiratory causes (Health Effects Institute, 2010), and airway inflammation (Shang et al., 2020).

Therefore, there has been growing interest in assessing whether professional drivers are disproportionately affected by air pollution (Knibbs & Morawska, 2012). Studies have found that taxi and truck drivers have higher pollution exposures compared to office workers (Baccarelli et al., 2014). However, the majority of professional driver

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occupational studies conducted to date have measured time-integrated particulate matter (PM) exposure, where a single average exposure is measured for the duration of a drivers shift (Pronk et al., 2009). While time-integrated measurements are useful for epidemiological studies, time-resolved monitors, which can measure at resolutions as low as one second, can provide specific information on the magnitude and determinants of exposure throughout the day and therefore can better formulate targeted strategies to reduce professional drivers' exposure. Furthermore, these occupational studies have often focussed on long-haul drivers, with few studies conducted in urban areas. To our knowledge, few studies have investigated urban professional drivers' exposure to traffic related pollutants at high time resolutions (Bos et al., 2021; Gany et al., 2017; Hachem, Bensefa-Colas, et al., 2020; Hachem et al., 2021; Hachem, Saleh, et al., 2020; Lee et al., 2015; Moreno et al., 2019; Riediker et al., 2003; Yu et al., 2018). These studies have been performed on a relatively small scale (50 drivers or less) and only focused on individual professional driving sectors (for example taxi or waste truck drivers). A better understanding of how much these workers are exposed to during their day, and what influences their exposures, across a range of professional driving sectors is needed.

The need for exposure studies to investigate professional drivers in Europe is particularly important due to the rapid dieselisation policy implemented in the 1990s, with diesel vehicles incentivised due to lower carbon dioxide emissions (Cames & Helmers, 2013). This policy resulted in 42% of European cars being diesel by 2018 (European Environment Agency, 2018), compared to only 4% of vehicles in the United States (Chambers & Schmitt, 2015). Diesel exhaust emissions have become of particular interest since the International Agency for Research on Cancer (2012) classed diesel engine exhaust as a class 1 carcinogen, determining that exposure increases the risk for lung and bladder cancer.

In practice, the precise measurement of diesel exhaust is difficult due to the complex mix of pollutants emitted from the tailpipe; however, the pollutant black carbon (BC) is often measured as a proxy (Health Effects Institute, 2010). As such, there have been a growing number of personal BC exposure studies (Delgado-Saborit, 2012; Dons et al., 2012; Louwies et al., 2015; Paunescu et al., 2017; Rivas et al., 2016), and several studies on BC exposures while commuting (Karanasiou et al., 2014; Merritt et al., 2019; Okokon et al., 2017; Rivas et al., 2017; Weichenthal et al., 2015). Commuter studies have also investigated a wide range of determinants contributing to in-vehicle exposure, including meteorology, traffic, road and vehicle characteristics (Karanasiou et al., 2014; Kaur et al., 2007; Tartakovsky et al., 2013). However, there is conflicting evidence to suggest which determinants are most influential in reducing in-vehicle exposures. Furthermore, there is uncertainty on whether these commuter studies, which typically focus on short commutes (1–2 h) on fixed routes during rush hour, reflect professional drivers' exposures (Knibbs & Morawska, 2012). Therefore, better exposure assessments are needed for this occupation.

To assess whether professional drivers are disproportionately exposed to traffic-related pollution, this study collected high time-resolved personal BC exposures across seven professional driving sectors in London. We aimed to characterise BC exposures of professional drivers as they go about their day, analysing similarities and differences in exposures between sectors and daily activities. We then identified the most pertinent determinants of exposure, which were used to formulate targeted exposure reduction strategies for the occupation.

2. Methods

2.1. Study area and participants

London was chosen as the study location due to its established traffic-related air pollution issues and the large number of professional drivers working within the city (Greater London Authority, 2018). London also has the worst levels of congestion in Europe (Koceva et al., 2016). The study focused on urban professional drivers predominantly within the

Table 1
Summary detail of participating drivers.

Organisation	Sector	Number of enrolled participants	Valid participant data	Number of shifts monitored	Dates of monitoring	Shift time	Generic Vehicle	Fuel type
Organisation 1	Bus	9	8	28	July 2019	Day	Bus	Diesel
Organisation 2	Courier	5	5	19	October 2018	Day	Van	Diesel
Organisation 3	Courier	9	7	18	November 2018	Day	Van	Electric
Organisation 4	Courier	6	6	19	December 2018	Day	Van	Diesel
Organisation 5	Emergency Services	19	19	70	April, May, June and August 2018	Day/Night	Ambulance	Diesel
Organisation 6	Emergency Services	20	20	64	November and December 2018, January, February, May, June and July 2019	Day/Night	Fire Appliance	Diesel
Organisation 7	Heavy Freight	8	8	32	February 2018	Day	Various Lorries	Diesel
Organisation 8	Heavy Freight	10	8	31	July and December 2018	Day	Skip Lorry	Diesel
Organisation 9	Heavy Freight	10	10	36	October 2018	Day	Skip Lorry	Diesel
Organisation 10	Taxi	10	10	34	April and May 2018	Day/Night	Taxi	Diesel or Hybrid
Organisation 11	Taxi	10	10	36	May and June 2018	Day/Night	Taxi	Diesel or Hybrid
Organisation 12	Utility Services	10	10	33	October and November 2018	Day	Small Van	Diesel
Organisation 13	Waste Removal	10	10	33	April, July and August 2018	Day	Waste Truck	Diesel
Organisation 14	Waste Removal	10	10	34	January and February 2019	Day	Waste Truck	Diesel
		146	**141**	**487**				

M25 (a ring road often used to determine London's outer geographic boundary), however some drivers had jobs where they were required to drive to other regional cities and towns.

Monitoring took place between February 2018 and July 2019 with a total of 146 drivers from 14 organisations being recruited into the study (Table 1). Bus, courier, emergency services, heavy freight, taxi, utility services and waste removal sectors were targeted to represent BC exposures across the professional driving occupation. While undertaking monitoring, participants were asked to fill in a short questionnaire which detailed their working hours, type of vehicle they drove, fuel used, predominant window position for each shift and if they were a smoker. Prior to participation in the study all participants signed a consent form approved by the King's College London BDM Research Ethics Subcommittee HR-16/17-4415.

2.2. Personal BC monitoring

The latest generation microAeth (MA) 300/350 (Aethlabs, San Francisco, CA, USA) were chosen to measure BC. Its predecessor the microAeth AE51 (Aethlabs, San Francisco, CA, USA) has been used universally for BC personal exposure studies to date (Delgado-Saborit, 2012; Louwies et al., 2015; Rivas et al., 2016). The advantages of this new device are that it has an automatic advance filter tape system; dual-spot technology, which eliminates the need to correct for the filter loading effect (Drinovec et al., 2015) and an in-built global positioning system (GPS).

In this study 11 devices were used, six MA 300 s and five MA 350 s. The devices have the same technical specifications, but the MA350 device casing can withstand outdoor conditions. The devices were set to record at 10 s intervals with flow rate at 100 m/s and wavelength at 880 nm. Measurements were averaged to one-minute measurements for analysis.

All devices were co-located on four occasions (approximately every four months) during the monitoring period with an AE22 Aethalometer (Magee Scientific, Berkley, CA, USA) at Marylebone Road monitoring station. This site was chosen as it experiences a similar pollution environment to the drivers, as the site is 1 m from a heavily congested six-lane 'A' road (Department for Environment, 2019a). Each co-location was run for a minimum of five days. Deming regression was used to obtain correction values for each device. The co-locations were averaged over the whole period to use a standardised correction factor over the monitoring campaign (Table S1). This was decided as there was no evidence that different correction factors were required for different seasons or that sensors drifted over time.

Each participant was asked to carry a monitor with them for four days (96 h, four work shifts) including at work, commuting and at home. The devices ran continuously over this period. The shifts were primarily day shifts starting around 6 am and finishing before 6 pm, however there were also some evening and night shifts monitored. At the end of each shift participants were asked to take the device home to charge. There were times where participants did not charge the devices and, in rare cases (seven participants), only one out of the four days monitoring was completed.

2.3. Activity identification

The GPS data collected were used to determine the type of activity each participant was undertaking. Previous personal exposure studies have often relied on diaries to determine participant activities (Delgado-Saborit, 2012), however this has been shown to be resource intensive and often due to participant fatigue, activities can be recorded incorrectly. GPS data can therefore be used to calculate travel speed and identify the location of each measurement to quantitatively allocate participant activity.

GPS papers were reviewed (Shen & Stopher, 2014; van Dijk, 2018) to provide applicable rules to determine when a participant was driving or not driving. A participant was deemed as not driving where there were more than 3 consecutive minutes less than 1.5 m/s AND more than 7 min of data points were within a 50 m radius over a 15 min rolling, OR if more than 20% of all monitored participants points were within a 200 m radius (this was to establish depot and home locations). All other points were deemed as representing a person driving. To test the accuracy of these rules a taxi driver was asked to fill out a time activity diary when they were driving and stopping for a two-day and four-day work period between 16 May to 11 June 2019 (SI. 2). These rules provided an accuracy of greater than 95% in correctly determining points when they were driving or not-driving.

2.4. Data analysis

A total of 146 participants were provided with monitors, however five participants had either a faulty instrument or declined to take part after receiving the monitor. Data was visualised by participant to observe general trends and to flag any unusual data such as wildly fluctuating concentrations or consistently negative values. A small proportion of data were flagged and removed from analysis, 2.4% relating to a faulty instrument and 2.4% relating to negative or fluctuating values.

After data processing and cleaning, each participant's data set comprised of one-minute resolution BC exposures. Activities for each minute were labelled as follows, during work hours and driving – *'at work driving'*, during work hours and stopped – *'at work not driving'*, outside of work hours and driving – *'commuting'* and outside of work hours and stopped – *'at home'* (this included times when the participant was stopped but may have not been at home, however this proportion of time was assumed to be minimal). These activity data were visualised geographically using Leaflet (Cheng et al., 2019) for each participant to assess for accuracy. There were six participants where GPS coordinates did not record, these activities were categorised as *'unknown'*. Additionally, there were 13 participants who chose not to take their monitor home so only their *'at work'* exposures are presented.

To characterise professional drivers' exposures, data were summarised by participant, for the total monitoring period and on a per shift basis. Statistical tests were performed in 'R statistics' (R Core Team, 2018). Due to non-normality (normality tested using the Shapiro-Wilk test), Wilcoxon Signed Rank tests were used to test significant differences between proportion of time spent and proportion of BC exposure for each activity. Kruskall Wallis H tests were run to assess mean rank differences between sectors and activities. *Post hoc* tests were run using pairwise Dunn's tests, using 'Holm' adjustment. BC exposure data were also compared using Spearman correlation analysis to Marylebone Road monitoring station (kerbside site) and North Kensington monitoring station (urban background site).

2.5. Mixed effect model analysis

Due to the lack of independence of the exposure dataset (*i.e.* exposure at time n is dependent on exposure at time n-1), mixed effects models were run to identify the determinants of *'at work driving'* exposure at a 1-minute exposure resolution. The high time resolution was chosen to identify highly transient time-specific determinants in exposures experienced by drivers.

The mixed effects models are presented as:

$$(bcdriving)_{ij} = \alpha + (participant)_i + \beta_n(fixedeffect)_{ij} + \cdots + \varepsilon_{ij}$$

Where i is the index of each participant, j is the index of the 1-minute average in-cabin BC exposure, background concentrations, driving speed or meteorological parameter, α represents the fixed mean exposure for all participants, $(participant)_i$ is the random effect of each participant, the β's are the fixed effects for each variable, and ε_{ij} is the residual. Details of the fixed effects determinants included in the model are summarised in Table S2.

The mixed effects models were run in 'R Statistics' using the 'lmerTest' package (Kuznetsova et al., 2017). Analysis of models was completed by running a model with combinations of fixed effects. The optimal model was chosen as the model with the lowest corrected Aikaike information criterion (AICc). Multicollinearity between variables was analysed using the variance inflation factor (VIF). Variables with VIF greater than 3 were removed from the model.

Despite the residuals violating homoscedasticity and drivers' exposures being non-normal, data were not log-transformed for the mixed effect models. It was decided that transformed data would not be included in the primary results due to the fact that the interpretation of fixed effects for logged data is suboptimal (Field & Wilcox, 2017). This is because a log transformation of the dependent variable would result in the back transformed coefficients expressed as a percent change for each fixed effect, making it difficult to interpret and compare effects between determinants against no obvious baseline value. However, for completeness a logged model is provided in Table S3 to demonstrate that interpretation of significant fixed effects were not altered due to non-transformation of the data.

While fixed effect estimates of mixed effects models are generally unbiased for large sample sizes (Hayes & Cai, 2007), the violation of homoscedasticity may cause bias in the calculation of standard errors and confidence intervals (Field & Wilcox, 2017). To address the homoscedasticity assumption, bootstrapping of standard errors was run on the mixed effects model using the bootMer function in R (Bates et al., 2015), using 2000 sample runs. Previous studies have found that linear regression model outputs with large datasets are robust to non-normal distributions (Pek et al., 2018; Schmidt & Finan, 2018). As such the model is presented untransformed with percentile bootstrap estimates for confidence intervals presented. Statistically significant variables were considered where $p < 0.05$.

3. Results

3.1. Personal BC exposure across different activities

In total 11,492 h of personal BC exposure data for 141 professional drivers were analysed (Table 2). The average exposure for participants was 2.0 ± 1.4 μg/m^3 (mean ± standard deviation). '*At work*' exposures (3.1 ± 3.5 μg/m^3) were 2.6 times higher compared to times *'not at work'* (1.2 ± 0.7 μg/m^3) ($p < 0.01$). Individual standard deviations were often higher than mean exposures indicating a large variability in exposures experienced throughout the monitoring period. There was a significant difference in exposure between activities ($p < 0.01$), with *post hoc* tests finding significant differences between all activities ($p < 0.05$) except '*at work driving*' and '*commuting*' exposures ($p = 0.54$). '*At work driving*' exposures (4.2 ± 4.7 μg/m^3) were 1.9 times higher compared to '*at work not driving*' exposures (2.2 ± 2.2 μg/m^3) and 3.8 times higher than '*at home*' exposures (1.1 ± 0.7 μg/m^3).

There was a substantial range in exposures experienced both between and within participants. The highest exposed participant had an average exposure of 10.6 μg/m^3 while the lowest experienced 0.5 μg/m^3. '*At work driving*' exposures had the largest range between participants with the lowest exposed participant, an emergency services worker, having an average exposure of 0.8 μg/m^3, while the highest exposed participant, a waste removal driver, had average exposure of 42.6 μg/m^3. Conversely '*at home*' had the smallest range of exposures between participants (0.1 to 5.2 μg/m^3).

Comparison of *'at work'* exposure to fixed monitors across the monitoring period found that average worker exposure was similar to the Marylebone Road kerbside monitoring site (Department for Environment, 2019a) (3.4 ± 1.7 μg/m^3) but had a weak correlation (Spearman's r = 0.19, $p < 0.001$). However, exposures were over three

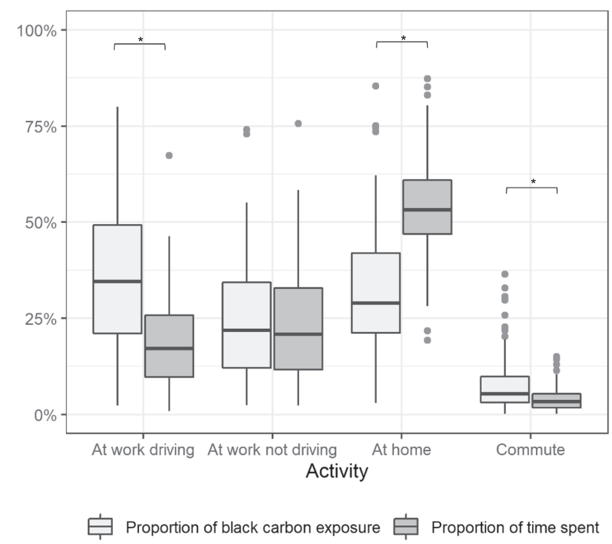

Fig. 1. Proportion of BC exposure and proportion of time spent on each activity by participants. Bold horizontal black lines denote the median proportion; boxes extend from 25th to 75th percentile; vertical lines indicate 1.5 times the interquartile range; with dots being proportions outside the range of these values. Statistically significant differences are according to the Wilcoxon Signed Rank Test, *, $p < 0.001$.

Table 2
Summary statistics by participant for mean, minimum, median and maximum BC exposures across different activities.

Activity	Number of participants	Mean (SD) for hours monitored	BC exposure (μg/m^3)				
			Arithmetic mean (SD) participant	Geometric mean (SD) participant	Minimum participant	Median participant	Maximum participant
At work driving	135	13.9 (9.5)	4.2 (4.7)	3.3 (1.9)	0.8	3.1	42.6
At work not driving	135	18.4 (11.1)	2.2 (2.2)	1.7 (1.9)	0.4	1.7	27.7
At work unknown	6	35.3 (12.9)	2.1 (0.8)	2.0 (1.5)	1.0	2.0	3.0
At work	**141**	**33.2 (10.8)**	**3.1 (3.5)**	**2.4 (2.0)**	**0.5**	**2.3**	**32.6**
Commuting	119	3.2 (2.4)	3.6 (2.5)	2.8 (2.1)	0.5	3.0	19.5
At home[#]	122	49.4 (34.9)	1.1 (0.7)	0.9 (1.7)	0.1	1.0	5.2
Not at work unknown	6	44.2 (19.2)	1.0 (0.3)	0.7 (1.7)	0.3	0.9	2.1
Not at work	**128**	**53.0 (34.3)**	**1.2 (0.7)**	**1.1 (1.7)**	**0.2**	**1.0**	**4.4**
All times	**141**	**81.5 (39.1)**	**2.0 (1.4)**	**1.7 (1.7)**	**0.5**	**1.6**	**10.6**

SD = standard deviation between participants.
[#] Thirteen participants only recorded *'at work'* exposures and did not take their monitors home.

times higher than concentrations at the urban background monitoring site located in North Kensington (Department for Environment, 2019b) (0.9 ± 0.8 μg/m^3).

3.2. Time-weighted exposure

On average, 18.6% of time was spent by the participants *'at work driving'*, but this contributed 36.4% of total BC exposure; while 54.4% of time was spent *'at home'*, but this only contributed 31.4% of total BC exposure (Fig. 1). Average *'commuting'* exposures were relatively high, but with only 4.0% of time spent in this activity, it only contributed 7.9% of total exposure. Despite spending only 42% of their time at work, this resulted in 61% of professional drivers total BC exposure.

3.3. Differences in exposures between driving sectors

Table 3 presents a summary of different exposures experienced across the professional driving sectors by shift. There was a significant difference between exposures across the various sectors for all times *'at work'* ($p < 0.01$), (*post hoc* test results in Table S4 – S6). The sectors broadly formed three groups; taxi drivers had significantly higher *'at work'* exposures compared to all other sectors, while courier, waste removal and heavy freight exposures were not significantly different to each other, but had significantly higher exposures compared to utility services, buses and emergency services. As some sectors were only monitored during certain seasons, differences in sector exposures subtracting background BC were also compared. However, BC exposures adjusted for background concentrations largely exhibited similar trends as unadjusted exposures (Table S8), apart from bus drivers' exposures having slightly higher adjusted exposures compared to utility services workers.

The trend in average *'at work'* exposures largely followed average *'at work driving'* exposures and time spent driving (Table 3). Taxi drivers spent 72% (6.5 h) of their shift driving and had the highest *'driving'* exposure, 6.6 ± 4.9 μg/m^3. While, emergency service and utility service workers spent the least amount of time driving during their shifts and were two of the three lowest sectors for *'at work'* exposure. Heavy freight and bus sectors spent the next longest time driving (6.1 h, 63% of shift time and 5.5 h, 69% of shift time respectively) however this did not relate to having higher exposures compared to courier and waste removal drivers, potentially indicating differences in driving location and characteristics between sectors.

Identifying the cause behind differences in exposures between sectors is complex, however the characteristics of each sector while *'at work driving'* can provide insight (Table S9). Taxi, couriers and waste removal drivers spent the highest proportion of time driving in central London (39.8% to 69.5%). These sectors also had the lowest average vehicle speed, greatest proportion of time driving within 50 m of traffic signals and the highest mean aspect ratio (>1) on roads driven, but also experienced lower car and HGV numbers compared to the other sectors. Heavy freight, utility services and emergency services largely worked in inner and outer London, while bus drivers taking part in this study drove 90.5% of their time outside of London. Most shifts monitored were during the day, including morning and evening peak traffic periods; however, emergency services spent a high proportion of time driving at night at 27.1%.

3.4. Characterising 'at work driving' exposures

Qualitatively visualising exposures at a high time resolution can provide an initial insight on the characteristics, magnitude and cause of high exposures experienced by professional drivers. Individual BC exposures were observed to be highly variable over the course of the day, with extended periods of low exposures, punctuated by intermittent periods of short extremely high spikes, at times exceeding 100 μg/m^3. These elevated exposures often occurred while driving. Increases in exposure while driving were rapid and remained entrapped within the vehicle cabin for between 10 min and an hour, before returning to previous levels (Fig. 2). There were also times where BC slowly accumulated or showed multiple spikes over a short time period. The fact that pollutants are 'transported' within the moving vehicle may partially obscure the cause of high exposure. From these examples it appeared that high exposures occurred in central London during periods in congested traffic; however, it was also noticeable that not all congested environments resulted in high exposure, further adding to the complexity in identifying the determinants of high exposures while driving.

3.5. Mixed effects model for 'at work driving' exposures

As driving resulted in the highest levels and proportion of BC exposure for professional drivers, a mixed effects model (Table 4) was run to identify variables that significantly influenced *'at work driving'* exposures. Background BC was a significant predictor for driving exposure with every 1 μg/m^3 increase in background concentrations resulting in a 0.5 μg/m^3 increase in driver exposure. There was a negative relationship between wind speed and drivers' exposure with a 1 m/s increase in wind speed resulting in an exposure decrease of 0.3 μg/m^3. All sectors except courier drivers were found to have significantly lower exposures than taxi drivers, which was used as a comparator. While there was a significant difference between exposures, confidence intervals were large, highlighting the variability in exposures experienced by drivers across all sectors. The effect of location was also significant, with lower drivers' exposures when moving away from the city centre. Inner London exposures were 0.2 μg/m^3 lower compared to Central London, while outside London exposures were 1.0 μg/m^3 lower.

Evening peak periods (17:00 to 19:59) resulted in significantly higher exposures (0.7 μg/m^3) compared to day time (10:00 to 16:59). However, the morning peak time (7:00 to 09:59) and night time exposures (20:00 to 06:59) were 0.3 μg/m^3 and 0.2 μg/m^3 lower respectively than day time exposures. There was also significantly lower exposure of 1.5 μg/m^3 for drivers working on the weekend compared to weekdays.

Table 3

Summary statistics of at work BC exposures and time spent for different sectors by shift. Sectors are ordered from highest at work exposure to lowest.

			Mean (SD) BC exposure (μg/m^3)				Mean (SD) time spent in hours			
Sector	**Participants**	**Shifts**	**At work driving**	**At work not driving**	**At work unknown**	**At work total**	**At work driving**	**At work not driving**	**At work unknown**	**At work total**
Taxi	20	70	6.6 (4.9)	3.5 (3.6)	–	**5.6 (4.3)**	6.6 (2.7)	2.5 (2.2)	–	**9.1 (2.4)**
Courier	18	56	5.5 (7.1)	2.9 (3.4)	–	**3.9 (4.9)**	3.7 (1.3)	5.2 (1.8)	–	**8.8 (1.3)**
Waste Removal	20	67	4.3 (7.1)	2.9 (3.2)	–	**3.7 (5.5)**	4.1 (1.4)	3.4 (2.1)	–	**7.4 (1.7)**
Heavy Freight	26	99	3.9 (2.2)	2.0 (1.3)	2.4 (1.2)	**2.9 (1.5)**	6.1 (2.3)	3.9 (1.8)	10.1 (1.8)	**9.7 (2.6)**
Utility Services	10	33	3.1 (2.1)	1.3 (1.0)	–	**2.0 (1.4)**	3.2 (1.7)	6.4 (2.6)	–	**9.5 (3.3)**
Bus	8	28	2.3 (0.8)	1.2 (0.5)	–	**1.9 (0.7)**	5.5 (2.0)	3.2 (1.5)	–	**8.0 (3.1)**
Emergency Services	39	134	2.8 (1.4)	1.4 (0.9)	1.0 (0.3)	**1.6 (1.0)**	2.1 (1.2)	8.8 (2.3)	13 (1.8)	**10.4 (2.5)**
Total	**141**	**487**	**4.1 (4.6)**	**2.2 (2.5)**	**2.1 (1.2)**	**3.1 (3.5)**	**4.3 (2.5)**	**5.3 (3.2)**	**10.6 (2.1)**	**9.3 (2.6)**

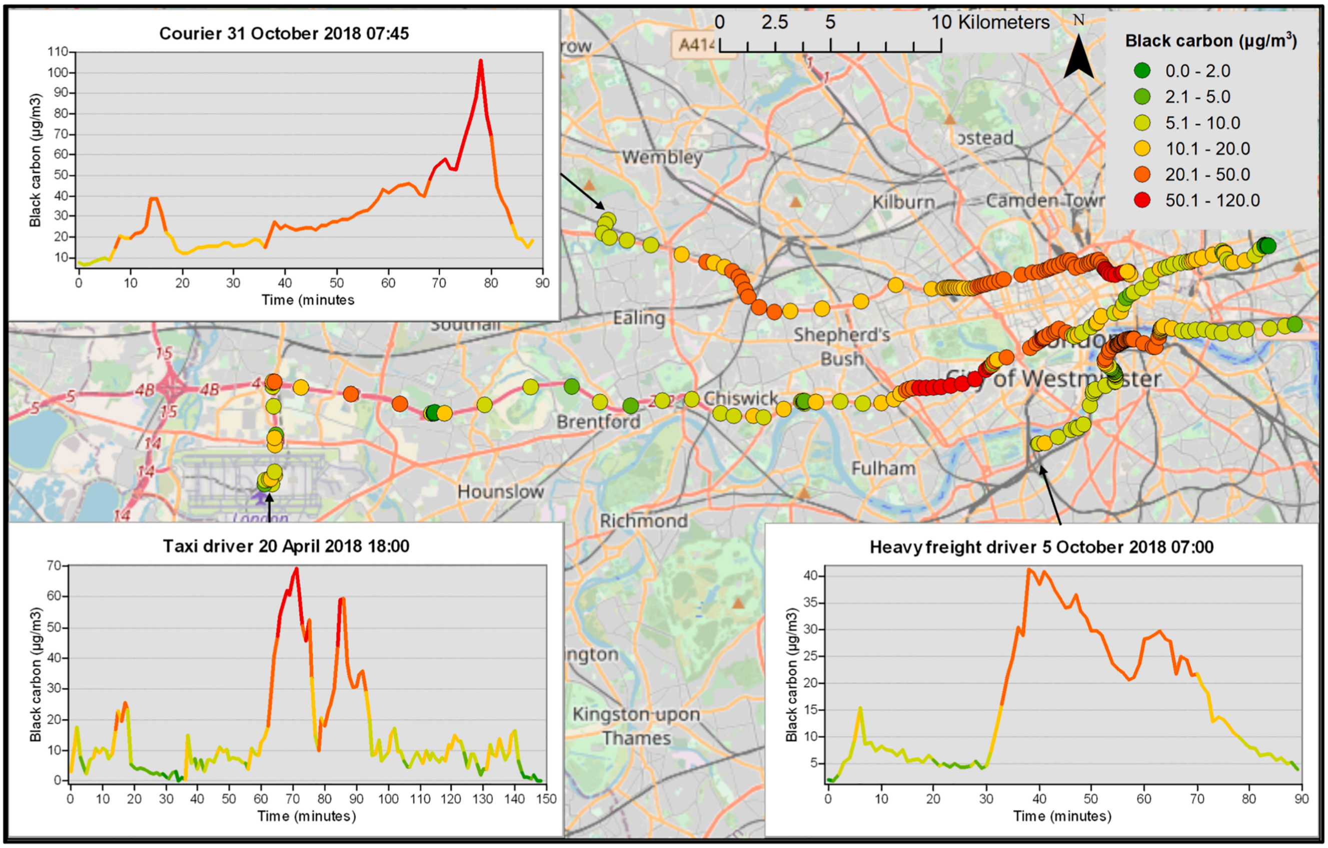

Fig. 2. Examples of high exposure events from a selection of participants while driving from west to east across London. Arrows point to starting position of each graph and titles indicate starting time of each event. Each point represents 1-minute of exposure, with bunching of points reflecting periods of congestion.

Fuel type was statistically significant between diesel and hybrid vehicles; however, as only hybrid vehicles were monitored for taxi drivers the 4.5 μg/m^3 lower exposure is a comparison between hybrid and diesel taxi drivers only. Also, important to note is the associated large confidence interval suggesting a large variation in exposures experienced in both types of vehicles. Window position results found a 0.3 μg/m^3 higher exposure for drivers who had their windows open for their shift compared to windows closed. There was no significant difference between exposures for smoker status apart from between those participants who did not report their smoking status and non-smokers.

The effect of aspect ratio, which is a measure of the depth of street canyons, found a 1-point increase in the building height to street width ratio resulted in a 0.2 μg/m^3 increase in driver exposure. Driving in tunnels had one of the largest elevated exposures to drivers with a 5.7 μg/m^3 higher exposure observed.

The model found there was no significant trend observed with number of cars, but there was a 0.1 μg/m^3 increase in driver exposure per increase of 1000 heavy goods vehicles and buses. Another indicator of congestion resulted in drivers having a 0.3 μg/m^3 higher exposure when within 50 m of traffic lights. However, there was no significant relationship found between vehicle speed and drivers' exposure. Road type was also observed to have a significant impact on exposures, with driving on 'A' roads, having significantly higher exposures compared to all other road types except for private roads.

4. Discussion

This study found that professional drivers were exposed to high levels of BC while at work, with elevated spikes in exposure occurring when driving. Time spent driving was an indicator of high average work exposure; however, there were some differences between professional driving sectors that could not solely be explained by driving duration, as the location and characteristics of the participant's work also appeared to influence exposure levels. Ambient BC, wind speed, sector, location, time of day, vehicle type, window position, congestion and urban infrastructure were found to significantly influence drivers' exposure. These results provided evidence for the formulation of targeted exposure reduction strategies for drivers.

4.1. Professional driver exposures compared to other groups

Results from this study found similar trends to previous personal exposure studies, with the lowest average exposures experienced in the home and higher exposures experienced while commuting (Li et al., 2015; Rivas et al., 2016). However, average exposures for participants in this study (2.0 ± 1.4 μg/m^3) were higher than the majority of other BC personal exposure studies conducted in urban Europe, where average exposure ranged between 0.9 and 1.6 μg/m^3 (Fig. 3) (Cunha-Lopes et al., 2019; Delgado-Saborit, 2012; Donaire-Gonzalez et al., 2019; Dons et al., 2011, 2012; Louwies et al., 2015; Nieuwenhuijsen et al., 2015; Pañella et al., 2017; Paunescu et al., 2017). Two studies in Europe measuring personal exposures of school children had higher levels than ours, at 2.7 μg/m^3 in Barcelona (Rivas et al., 2016) and 5.1 μg/m^3 in Cassino, rural Italy (Buonanno et al., 2013). It is important to note that these European personal exposure studies were largely conducted between 2010 and 2013, and since this time there has been a large reduction in kerbside BC levels at ~0.8 μg/m^3 per year in London (Hessey et al., 2017). Therefore, our results do suggest that professional drivers are likely to be disproportionately affected by BC exposure due to their occupation compared to the general population in urban European cities.

Other personal BC exposure studies in Asia, South America and Africa, often reported higher exposures than this study, with BC exposure

Table 4
Fixed effects estimates from mixed effects model for drivers' black carbon exposures in London.

Fixed effect	Categorical comparison	Estimate	Percentile bootstrap 95% CI (lower, upper)	*p-value*
(Intercept)		8.677	6.202, 11.095	<0.001
Background Black Carbon (μg/m^3)		0.524	0.452, 0.594	<0.001
Wind speed (m/s)		−0.299	−0.335, −0.265	<0.001
Sector	Bus ~ Taxi	−5.291	−9.959, −0.889	0.02
	Courier ~ Taxi	−2.704	−6.235, 0.940	ns
	Emergency Services ~ Taxi	−5.513	−8.292, −2.488	<0.001
	Heavy Freight ~ Taxi	−4.986	−8.049, −1.686	0.003
	Utility Services ~ Taxi	−5.400	−9.419, −1.488	0.008
	Waste Removal ~ Taxi	−4.609	−7.899, −1.397	0.007
Location	Outside ~ Central London	−1.004	−1.332, −0.700	<0.001
	Outer London ~ Central London	−0.300	−0.494, −0.103	0.01
	Inner London ~ Central London	−0.229	−0.36, −0.092	0.001
Vehicle Speed (km/hr)		0.003	0.000, 0.006	ns
Time of day	Night time ~ Day time	−0.273	−0.447, −0.110	0.001
	Morning peak ~ Day time	−0.290	−0.410, −0.167	<0.001
	Evening peak ~ Day time	0.717	0.577, 0.856	<0.001
Day of week	Weekend ~ Weekday	−1.473	−1.670, −1.276	<0.001
Fuel type	Electric ~ Diesel	−0.766	−4.780, 3.461	ns
	Hybrid ~ Diesel	−4.490	−9.004, −0.156	0.05
Predominant window position	Not reported ~ Window closed	0.848	−0.623, 2.349	ns
	Windows open ~ Windows closed	0.310	0.126, 0.502	0.001
Smoker Status	Not reported ~ Non-smoker	5.238	1.680, 8.644	0.004
	Smoker ~ Non-smoker	2.133	−0.330, 4.676	ns
Aspect ratio (H/W) by road		0.193	0.088, 0.308	0.001
Tunnel	In tunnel ~ Not in tunnel	5.669	4.684, 6.675	<0.001
Number of cars ('000) by road		0.001	−0.002, 0.004	ns
Number of HGV ('000) by road		0.137	0.104, 0.170	<0.001
Number of buses ('000) by road		0.131	0.092, 0.168	<0.001
Distance to traffic signal	Within 50 m ~ Greater than 50 m	0.298	0.197, 0.402	<0.001
Road type	Motorway ~ 'A' Road	−1.104	−1.370, −0.824	<0.001
	'B' Road ~ 'A' Road	−0.778	−0.944, −0.606	<0.001
	Minor Road ~ 'A' Road	−0.344	−0.485, −0.198	<0.001
	Local Street ~ 'A' Road	−0.454	−0.652, −0.255	<0.001
	Private Road ~ 'A' Road	0.386	−0.404, 1.155	ns

H/W – height of buildings divided by width of street, HGV – Heavy goods vehicle, ns- not significant.

between 1.9 and 18.6 μg/m^3 (Fig. 3) (Baumgartner et al., 2018; Carvalho et al., 2018; Curto et al., 2019; Downward et al., 2016; Du et al., 2010; George et al., 2020; Jeong & Park, 2017; Lei et al., 2016; Lin et al., 2020; Pant et al., 2017; Sanchez et al., 2020; Secrest et al., 2016; Van Vliet et al., 2013; Zhao et al., 2014; H. Zhou et al., 2020; Y. Zhou et al., 2020). These countries have other sources of pollution such as coal and biomass burning for heating and cooking, and older vehicle fleets which can lead to higher BC levels (Salako et al., 2012). Conversely, studies in North America and Australia reported some of the lowest BC exposures (0.4 to 1.8 μg/m^3) (Jung et al., 2017; Koehler et al., 2019; Lovinsky-Desir et al., 2016; Quinn et al., 2018; R. Williams et al., 2012; R. D. Williams & Knibbs, 2016; Zamora et al., 2018), possibly indicating the lower number of diesel vehicles in these countries and absence of other BC sources (Briggs & Long, 2016; Chambers & Schmitt, 2015).

Comparing our professional drivers time-weighted exposures to studies on populations with a fixed place of work, Dons et al. (2012) found participants spent 17% of time at work, but this only contributed 12% of their total BC exposure. The high contribution of BC exposure from *'at work driving'* (36% of BC exposure compared to 19% time spent) further highlights the fact that professional drivers are disproportionately exposed to BC due to the time they spend driving.

4.2. 'At work' exposures and differences between sectors

Personal *'at work'* exposures in this study were three times higher than background and equal to kerbside monitors. In comparison, other personal exposure studies have found that the indoor workplace is typically a low exposure environment with lower exposures experienced compared to ambient monitor concentrations (Carvalho et al., 2018; Koehler et al., 2019). In addition, the variation and magnitude of exposures recorded at the fixed monitors did not reflect the significant variability in exposures experienced by drivers, reiterating the need for personal exposure studies to better reflect populations' exposures.

'At work' exposures were low (3.1 ± 3.5 μg/m^3) compared to the small number of personal BC professional driver studies conducted. Du et al. (2011) reported average 24-hour BC exposures for 20 taxi drivers (15.4 μg/m^3) in Beijing. Other studies found average shift exposures of 9.1 μg/m^3 for 17 waste truck workers in Korea (Lee et al., 2015) and 63.9 μg/m^3 for seven bus drivers in Nairobi, Kenya (Ngo et al., 2015). Four studies measured occupational exposures which were comparable to our study, taxi drivers in New York, Lebanon, Paris and Barcelona had shift exposures ranging from 1.9 to 6.5 μg/m^3 (Gany et al., 2017; Hachem, Bensefa-Colas, et al., 2020; Hachem, Saleh, et al., 2020; Moreno et al., 2019).

Despite the lower exposures measured for professional drivers in this study, epidemiological studies have found adverse health effects associated with small increases (~1.5 μg/m^3) in ambient BC (Maynard et al., 2007; World Health Organisation, 2012). While, other studies have found adverse heart rate variability measures for participants after undertaking a two hour commute (Chuang et al., 2013; Sarnat et al., 2014). Driving exposures in this study were at times observed to exhibit very high exposures for periods of up to an hour. Notably, similar concentrations of diesel exhaust PM in chamber studies have been shown to induce acute inflammation in human airways (Behndig et al., 2011). Spikes in exposure have previously been noted to occur in transport (Dons et al., 2019; Lim, Dirks, et al., 2015), although they were not identified at such high levels. Reducing the occurrence and the duration of exposure spikes is likely to substantially reduce driver exposure and warrants further investigation.

Potential explanations for the differences in exposures observed between sectors were largely due to driving duration and characteristics linked to work location and congestion; commuter exposure studies have identified these factors to result in higher exposures previously (Dons et al., 2013; Li et al., 2015; Zuurbier et al., 2010). Taxi drivers

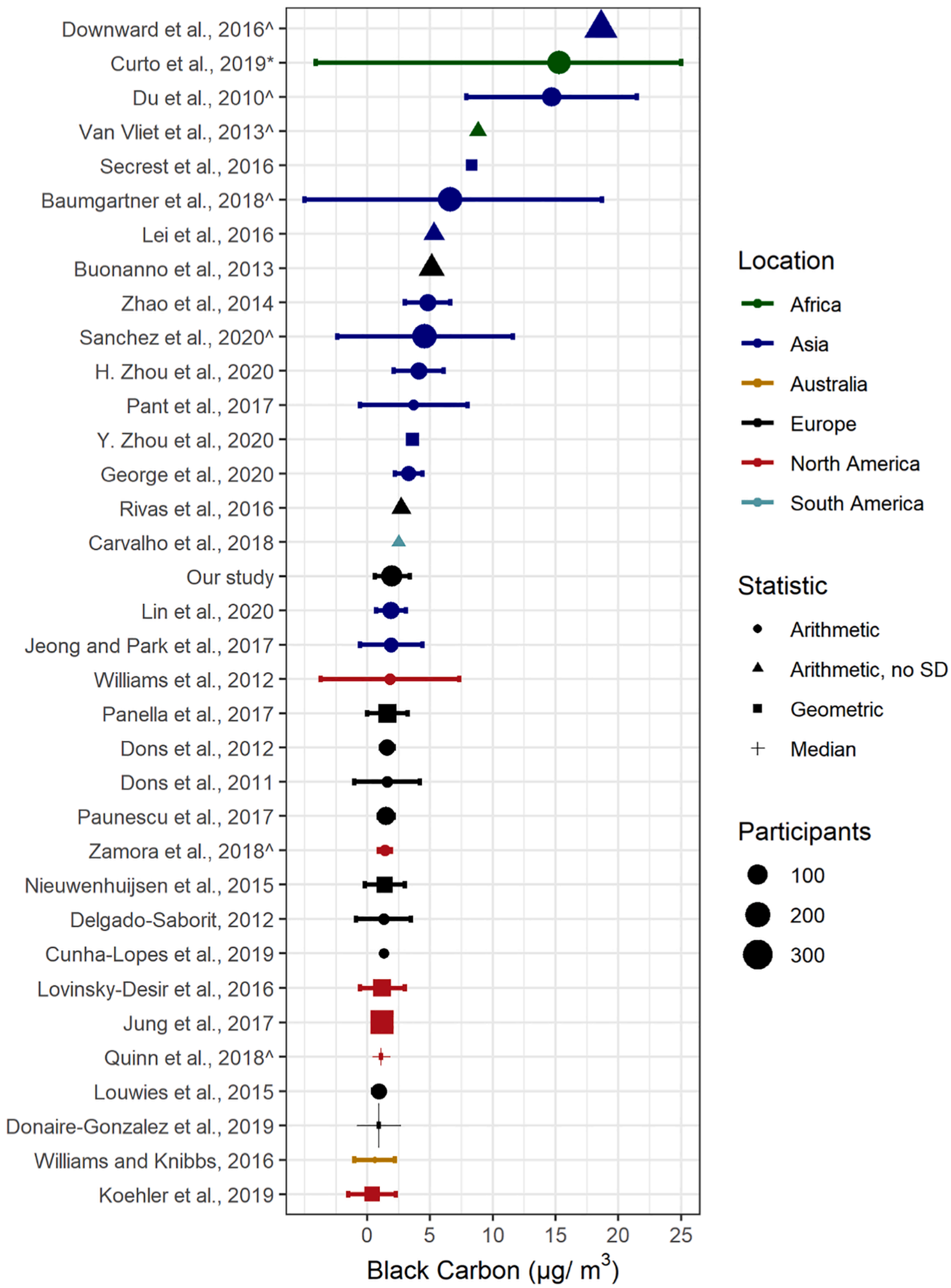

Fig 3. Comparison of our study results to 34 other BC personal exposure studies, minimum monitored time for each participant is 18 h. Studies are ordered from highest mean exposure to lowest, error bars indicate ± SD. Curto et al., 2019* results were 15.3 ± 19.4 μg/m^3, but the axis excluded >25 μg/m^3. All studies used time-resolved monitors (microAeth AE51, Aethlabs) except studies flagged with ˆ, these studies used time-integrated monitors. Participants indicate number monitored in study.

spent most of their time driving in central and inner London, dropping and picking up passengers in congested areas, leading to the highest exposures (5.6 μg/m^3). While couriers and waste removal drivers also spent a large proportion of their time driving in central London, they spent less time driving compared to taxi drivers and therefore had slightly lower shift exposures (3.9 μg/m^3 and 3.6 μg/m^3). Although taxi, couriers and waste removal drivers worked on roads that had lower vehicle numbers compared to other sectors, central and inner London is often more congested due to a lower road capacity compared to outer London (Bradley, 2017). Heavy freight had statistically similar exposures (2.9 μg/m^3) to couriers and waste removal drivers, as although they spent a high proportion of time driving in outer London in free-flowing traffic, they spent a longer period of their shift driving. The lowest work exposures were experienced by emergency service and utility service workers which was largely related to the short period of time spent driving during their shift. Bus drivers also recorded low exposures despite spending a large proportion of their shift driving, however this was thought to be due to this sector being based on the outskirts of London where there is less congestion.

4.3. *Determinants of professional drivers' BC exposures*

The determinants tested in the mixed-effects model have been observed to some degree in previous commuter exposure studies (Dons et al., 2013; Li et al., 2015; Tartakovsky et al., 2013; Tunno et al., 2016; Yu et al., 2018). However, driver exposure in most of these studies was measured on a fixed route and the vehicle driven simulated expected commuting behaviour, so it was important to assess whether these determinants were also reflected in professional driver exposures.

4.3.1. *Determinants of exposure outside of the drivers' control*

Ambient BC, wind speed, sector, and location, were found to have a significant influence on drivers' exposures, however there is little that drivers can practically do to control these determinants. Ambient BC has been found to have a significant influence on personal BC exposures previously (H. Zhou et al., 2020). While the effect of ambient concentrations in this study appeared relatively high, with a 0.5 μg/m^3 exposure increase per 1 μg/m^3 increase in ambient BC, the third quartile background BC in this study was only 1.1 μg/m^3, so the absolute effect on exposure was comparatively small. Wind speed was found to have a significant negative relationship with drivers' exposure, this was hypothesised as an increase in wind speed would aid dispersion of BC (Hachem, Saleh, et al., 2020; Kaur et al., 2007). The location of where the participant drove was also an important determinant with the highest exposures experienced in central London due to the higher congestion in this location.

4.3.2. Reducing exposures through drivers and employers

Out of all determinants analysed, the easiest way for drivers to immediately reduce their BC exposure would be to drive with closed windows. Driving with windows closed has been observed to reduce in-cabin traffic-related concentrations in studies previously (Li et al., 2015; Moreno et al., 2019; Yu et al., 2018). The study also found time of day to significantly influence BC exposures with lower exposures in the morning peak and night compared to day time, likely reflecting the unique nature of London having consistently high vehicle numbers throughout the day (Broaddus et al., 2015). There were also lower exposures found for drivers working on the weekend compared to the weekday, again thought to be due to the lower vehicle numbers on weekends. Other studies have previously found elevated exposures when vehicle numbers are at their highest, typically in the morning and evening peak (Dons et al., 2013; Kaur et al., 2007; Li et al., 2015). Drivers of hybrid taxis were found to have lower BC exposures compared to diesel taxis. While fuel type has been noted to affect in-cabin PM exposures in other studies (Moreno et al., 2019; Zuurbier et al., 2010), it is thought fuel type did not directly affect exposures in this case, but that reduced air exchange rates due to cabin design in the hybrid taxi caused the decrease in BC exposure (Bos et al., 2021).

The results suggest that employers could assist with reducing BC exposure for their drivers, by providing vehicles with more air-tight cabins, encouraging driving with closed windows and moving shifts to early morning, night or the weekend where possible.

4.3.3. Reducing drivers' exposures through policy

Distance from traffic lights, road type, vehicle number and vehicle speed were included as proxies for congestion in the model. All variables apart from vehicle speed indicated a positive association between congestion and drivers' BC exposure. Drivers on 'A' roads, which are known to be the most congested roads in London (Chow et al., 2014) had the highest exposures compared to other road types. While the lowest exposures were found for drivers on motorways, assumed to be due to the free-flowing traffic on these roads. Other studies have previously suggested elevated exposures on roads with congestion (Dons et al., 2013; Patton et al., 2016), with stop start and idling traffic causing increased tailpipe emissions which can infiltrate into the cabin. While average car numbers by road did not significantly influence in-cabin exposure, the number of buses and heavy vehicles was found to increase exposure. This accords with studies suggesting these vehicles have the highest emissions (Tunno et al., 2016), and therefore could increase drivers exposures when they are in close proximity. A possible reason why vehicle speed was not observed to have a significant effect on drivers' exposure was that higher driver BC exposures have been observed at both low and high vehicle speeds (Dons et al., 2013; Karanasiou et al., 2014). Some studies suggest that lower vehicle speeds are thought to indicate higher levels of congestion and therefore BC exposure (Dons et al., 2013; Lee et al., 2015). While others have found at high speeds the vehicles air exchange rate increases, enabling fine PM to infiltrate into the cabin (Yu et al., 2018).

Higher aspect ratios and driving in tunnels were also associated with increased driver exposure, with driving in tunnels being the determinant which increased exposures the most. These results suggest that the accumulation of pollutants in deep street canyons and tunnels (Knibbs et al., 2011; Krzyżanowski et al., 2005) enter vehicle cabins when driving on roads with these features.

At a local scale, policies to decrease congestion, restricting the number of heavy goods vehicles and buses, reducing emissions from these vehicles and introducing regulations to improve the dispersion of pollutants in street canyons and tunnels would significantly reduce exposures for professional drivers. While some of these policies have been implemented in cities around Europe (European Commission, 2016; Holman et al., 2015), this study further adds to the evidence base and importance of such strategies to reduce not only ambient pollution levels but also drivers exposures.

4.4. Strengths and limitations

To our knowledge this is the largest study of its kind to characterise and analyse determinants of professional drivers BC exposure in urban settings. Personal exposure studies are not typically analysed at one-minute exposure levels, however the benefit of doing so enabled us to highlight geographic and time-specific determinants of exposure while driving.

The study had some limitations. We did not model peak exposures in our mixed effects analysis, which may have important health implications. While we tried to identify determinants that could be independently verified, some variables such as window position relied on participants self-reporting and compliance could not be guaranteed. Simultaneous carbon dioxide measurements would have provided a cross-check on these variables and we are now including this check in future research. We also had difficulty recruiting some important professional driving sectors (such as bus drivers in Central London) and therefore could have missed some pertinent sector-specific interventions. While we monitored a wide range of sectors, there also appeared to be sector specific characteristics that caused variation in drivers' exposures that are still not well understood. The introduction of multiple sectors in several locations may have diluted the strength of suggested interventions. A more focused study on each sector may provide more specific interventions such as the effect of vehicle make and age on drivers' exposures.

5. Conclusion

This study is one of the first to provide a detailed characterisation of professional drivers' BC exposures for a range of sectors across different activities throughout their day. The study found that professional drivers are disproportionately exposed to BC, due to the prolonged time spent in the transport microenvironment and at times were exposed to extremely high spikes of BC. Time spent *'at work driving'*, resulted in the highest levels and proportion of BC exposure experienced by participants throughout their day with average exposure being twice as high compared to time spent *'at work not driving'* and four times higher compared to when participants were *'at home'*. The results highlighted that taxi, couriers, waste removal and heavy freight drivers had the highest exposures due to the time spent driving and the location of their work in central congested areas. Therefore, these sectors should be prioritised to reduce their exposure. The determinants analysis found that driving in tunnels, congestion, location, day and time of shift had the most significant effect on drivers' BC exposures and provided an insight into strategies which could be implemented to reduce exposure. With the increased health risk to professional drivers, there is a responsibility and duty of care from their employers alongside policy makers to reduce their BC exposure. Therefore, targeted exposure reduction strategies such as ones suggested in this study should be implemented and further studies on the associated health effects of traffic-related pollution exposure on professional drivers are needed.

CRediT authorship contribution statement

Shanon Lim: Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft. **Benjamin Barratt:** Conceptualization, Methodology, Validation, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Lois Holliday:** Investigation, Writing - review & editing. **Chris J. Griffiths:** Supervision, Writing - review & editing. **Ian S. Mudway:** Conceptualization, Methodology, Validation, Supervision, Project administration, Writing - review & editing, Funding acquisition.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2021.106532.

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