The Driver Diesel Exposure Mitigation Study (DEMiSt)

Report submitted to the IOSH Research Committee

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Abstract

Diesel exhaust is a known carcinogen and has been linked to a range of cardiovascular and respiratory health problems. Previous exposure studies have found individuals are most highly exposed to this pollutant while commuting. However, while most people spend one to two hours in the commuting environment each day, few studies have considered the exposures experienced by urban professional drivers who are required to drive in this environment for the majority of their working day.

The overarching aim of this project was to quantify the risk of harm to professional drivers in urban settings from exposure to diesel exhaust, allowing for the formulation of risk reduction strategies. To achieve this, we have conducted the largest real-world in-vehicle personal exposure study to date. The baseline study monitored 141 drivers based within London for four working days across a variety of professional driving sectors. A follow-up intervention study of 42 drivers was conducted to assess the effectiveness of using in-cabin filters to reduce drivers' exposure.

The results demonstrated that urban professional drivers are disproportionately affected by diesel exhaust exposure, because they spend on average more than four hours of their day driving. Average *'at work driving'* exposures were 3.8 times higher compared to *'at home'* exposures and 1.9 times higher than *'at work not driving'* exposures. Sectors which spent a higher proportion of their shift driving, such as taxi drivers, had higher work exposures compared to those sectors which drove intermittently.

We found that drivers could reduce their exposure by driving with their windows closed, reducing times driving on weekdays in the evening peak and by avoiding heavily congested areas, including central London and tunnels. We also found evidence that different vehicle types could reduce exposure, particularly ones that had relatively airtight cabins. However, there was inconclusive evidence on the effectiveness of using in-cabin filters to reduce exposure. We make a series of recommendations based on the study results to ensure best practice for fleet operators in reducing drivers' exposures.

Executive Summary

Introduction

There is a wealth of data demonstrating that exposure to traffic-related pollutants is associated with negative health impacts. In particular, diesel exhaust is a known carcinogen and has been linked to a range of cardiovascular and respiratory health problems. While these associations have been identified in the general population, existing studies have missed one very significant exposure group: the vehicle drivers themselves. Professional drivers, particularly those working in congested urban settings, are likely to be disproportionately affected by diesel exhaust exposure due to the amount of time they spend driving during their working day.

Current research on in-vehicle driver exposures has predominantly focused on commutes to and from a fixed place of work, in morning and evening rush hours. The results of these studies show a large variation in traffic-related air pollution experienced by drivers while commuting. This suggests there is a need for specific studies focusing on professional drivers to better understand their unique working environment and highlight what interventions can be implemented to reduce their exposure to these pollutants.

Objectives

The overarching aim of the project was to quantify the risk of harm to urban professional drivers from exposure to diesel exhaust, allowing for the formulation of risk reduction strategies.

This aim was achieved by focusing on a series of objectives:

- to conduct a baseline study to assess the exposure of professional drivers in the working and home environment
- to characterise of drivers' exposure
- to identify determinants of drivers' exposure
- to trial and evaluate intervention methods on a subset of professional drivers
- to establish a database of drivers' exposures to support future evaluations.

Methods

As diesel exhaust is difficult to measure in practice, the pollutant black carbon (BC) was measured as a proxy. It is derived predominantly from diesel engines in the urban environment and has been found to be one of the most harmful components within ambient particulate matter.

The study was conducted in two stages:

- A baseline study of 141 drivers based in London examined exposures over four working days across various professional driving sectors. This was conducted from February 2018 to July 2019 to characterise and provide insight into the determinants of driver exposure
- An intervention study of 42 drivers was completed from June to September 2019 to assess the effectiveness of in-cabin filters in reducing driver exposure.

Participants were recruited in groups of five or ten drivers by approaching a gatekeeper at each organisation. The professional driving occupations targeted were taxi drivers; couriers; waste removal, heavy freight and bus drivers; utility services; passenger transport; and emergency services.

Black carbon exposures were measured by providing each driver with a portable microAeth (MA) 300/350, which has an in-built GPS. Exposures were measured for 96 continuous hours with monitors placed inside the vehicle cabin for the duration of their working day. Participants also carried the monitor with them outside of work hours. Prior to deployment, all devices were co-located with a reference monitor at the London Marylebone Road reference site to ensure accuracy. Data were audited by visualising data to observe general trends and to flag any unusual data such as wildly fluctuating concentrations, or consistently negative values. In total 9per cent of data collected were not considered for further analysis.

Each participant's data set comprised of one-minute resolution BC concentrations, with date and time, GPS coordinates, speed and bearing. Each one-minute point was labelled to show whether the participant was at work or not, what shift the participant was on, the predominant vehicle ventilation setting and window position for the shift, the vehicle type and whether or not the participant was moving based on GPS stratification. Activities were labelled as follows: '*At work driving' (*during work hours and moving); '*At work not driving'* (during work hours and stopped); '*Commuting'* (outside of work hours and moving); and '*At home' (*outside of work hours and stopped).

Determinants were used to identify the cause of high exposure for drivers, both individually and in a mixed-effects model, where the participant was included as the random effect. Determinants included in the analysis were: ventilation settings, window position, generic vehicle type *(ie van, truck, taxi, etc)*, vehicle speed, time of day, weekday or weekend, season, sector, fuel type, make and model of vehicle, whether or not measurements were made during school holiday periods, whether or not the participant was a smoker, geographical location, meteorological parameters and background BC concentrations. Determinants were first analysed individually, with both absolute measured BC and after adjustment for background concentrations. This adjustment removed the diurnal variation in ambient BC in order to analyse the specific effect of each determinant.

Results

In total, 11,492 hours of professional drivers' exposure data were analysed in the baseline monitoring campaign. The average overall exposure for participants was 2.0 ± 1.4 μg/m^3. *'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) ($p < 0.05$) and 3.8 times higher than *'at home'* exposures (1.1 ± 0.7 μg/m^3) ($p < 0.05$). On average, 18.6 per cent of the participants' time was spent *'at work driving'* but this contributed 36.1 per cent of total BC exposure, while 54.4 per cent of time was spent *'at home'*, though this only contributed 31.8 per cent of total BC exposure. There was a wide range of exposures experienced for individual participants, both within and between different activities, highlighting the complexity of characterising exposures within this mobile population. The highest exposed sectors while driving were taxi drivers (6.6 μg/m^3), couriers (5.5 μg/m^3) and waste removal drivers (4.3 μg/m^3), possibly reflecting the fact their work is predominantly undertaken within congested, elevated pollution areas in central London.

Spatial and temporal analysis of *'at work driving'* exposures identified the occurrence of exposure spikes which, at times, were above 100 μg/m^3 and appeared to remain trapped within the vehicle cabin for long periods. These spikes often occurred in congested traffic within central London and in areas where vehicles congregate, such as in car parks or depots.

The mixed effects model showed that driving with windows open resulted in a 0.44 μg/m^3 increase in driver exposure compared to windows closed, while there was a 0.60 μg/m^3 increase during evening peak times compared to daytime exposures, with a 1.35 μg/m^3 decrease in exposure when driving on a weekend compared to weekdays. Other determinants, such as wind speed, vehicle speed and background BC concentrations, were also significant determinants of driver exposure, although they had a minor influence compared to the factors mentioned above. Recirculate ventilation settings also appeared to reduce exposure compared with other ventilation modes when windows were closed. The type of vehicle was also found to affect driver exposure. While further work is needed to evaluate the specific cause of this difference, it is likely that better designed airtight cabins can significantly reduce drivers' exposure.

Overall, BC concentrations recorded during the intervention study were lower than the baseline study. These lower concentrations could relate to several factors, including the specific mix of sectors monitored for interventions, the introduction of the Ultra-Low Emission Zone in London in April 2019 and seasonal bias (the intervention study being conducted in spring and summer 2019).

The findings on the effectiveness of in-cabin filters to reduce drivers' exposure to BC were inconclusive. There appeared to be situations where, despite using the in-cabin filters, driver exposures were very high, as observed with two participants. When these high exposure participants were removed from analysis, the results revealed a significant reduction for *'at work driving'* exposure when using in-cabin filters, with the mixed effects model indicating a decrease of 0.40 μg/m^3 for a shift.

Conclusions

We have conducted the largest real-world in-vehicle personal exposure study to date. The study found that professional drivers are disproportionately affected by diesel exhaust exposure, with *'at work driving'* activity contributing most to daily exposure.

In several countries, exposure to hazardous substances, including diesel exhaust, is covered by law. In the United Kingdom, employers have a legal duty to consider the risk of cancer to their employees from work activities and, if there are activities of concern, they must act to reduce this risk. Therefore, organisations with professional drivers need to implement changes to mitigate against exposure to diesel exhaust.

Recommendations

The most effective way to reduce drivers' exposures to diesel exhaust is to change to zero tailpipe emission vehicles with airtight cabins. This will not only reduce drivers' exposures but will also reduce ambient concentrations, which will provide health benefits for the general population.

The following additional recommendations are made as a result of this study:

- The single simplest change drivers can make to reduce their exposure is to drive with the windows closed at all times
- Drivers should use the recirculate ventilation setting with windows closed. However, this setting should only be used for short periods in high pollution areas, due to the risk of elevated CO_2 caused when using this setting
- Route choice should be carefully considered to avoid areas and periods of high congestion. Avoiding tunnels will also assist in reducing drivers' exposure.
- Reducing the frequency of driving during the evening peak period (between 16:00 and 19:00) will decrease drivers' exposures
- Moving shifts from weekdays to weekends will also reduce drivers' exposures.
- If there are jobs which are likely to cause significantly higher exposure levels, consideration should be given to rotating drivers to avoid any single worker experiencing significantly higher levels of exposure compared with others
- In-cabin filters in certain circumstances may reduce drivers' exposures
- Employers should conduct training and provide information on diesel exhaust exposure. This should be included in induction and refresher training courses so that the impact of diesel exhaust exposure can be minimised.

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Abbreviations

Abbreviation	Meaning
BC	Black carbon
CI	Confidence interval
CO	Carbon monoxide
CO_2	Carbon dioxide
EC	Elemental carbon
GPS	Global positioning system
NO_2	Nitrogen dioxide
PM_1	Particulate matter with diameter less than 1 μm
PM_{10}	Particulate matter with diameter less than 10 μm
$PM_{2.5}$	Particulate matter with diameter less than 2.5 μm
UFP	Ultrafine particles, particulate matter with diameter less than 0.1 μm

1. Introduction

1.1 The health effects of traffic-related air pollution

There is a wealth of data demonstrating that exposure to traffic-derived pollutants or residential proximity to busy roads is associated with a range of negative health impacts, including increased cardiopulmonary mortality and hospitalisation for cardiac and respiratory causes[1] impaired lung development[2] and slowed cognitive development in children[3]. Recent time series studies undertaken in London (2011-2012), which examined the short-term relationship between exposure to traffic-specific markers (exhaust and non-exhaust) and cardiopulmonary mortality and morbidity, clearly demonstrated significant associations, predominantly with markers (black and elemental carbon) of diesel exhaust[4,5]. While these associations have been identified in the general population, existing studies have missed one very significant exposure group: vehicle drivers themselves. As vehicle pollutant concentrations attenuate rapidly with distance from the road[6], drivers are particularly vulnerable to high exposure from traffic-related pollution. Yet there are few studies that have addressed this and those employees who are required to drive for long periods as part of their occupation are likely to be disproportionately affected by the health risks of traffic-related air pollutants when compared to the general population.

This concern for professional drivers is reflected in the Institution of Occupational Safety and Health's 'No Time To Lose' campaign[7], which highlights the risk of occupational cancer caused by workplace activities; a chief focus is the exposure to diesel engine exhaust. Diesel exhaust is listed as a class 1 carcinogen by the International Agency for Research on Cancer[8], determining that exposure to it increases the risk of lung cancer and possibly bladder cancer. Furthermore, the current evidence drawn from experiments where subjects have been exposed to idling diesel fumes in experimental chamber studies, shows adverse physiological responses from participants, including altered lung function, inflammation and impacts on cardiovascular function[9].

1.2 Measuring in-vehicle driver exposures and their determinants

Studies that have investigated diurnal patterns of an individual's exposure consistently show that the commuting period of an individual's day results in the highest air pollution exposure[10-13]. However, existing research on in-vehicle driver exposures has predominantly focused on commutes to and from a fixed place of work in morning and evening rush hours. Recent improvements in technology, which have enabled smaller monitors, has made this type of research viable, with portable air pollution monitors being placed in vehicles to reveal occupants' exposures. There have been a few review papers focusing on drivers, commuting exposures, with the majority of studies taking place in Europe or North America, plus some recent studies in Asia[14-18]. The results of these studies show a large variation in traffic-related air pollution experienced by drivers while commuting, suggesting a need for more specific studies focusing on professional drivers in order to better understand their unique working environments.

Studies have suggested a wide range of determinants contributing to in-vehicle exposure, including weather, season, fuel type, ventilation settings, traffic levels, air filters, driver behaviours, proximity to pollution sources, dispersion of emissions in roads and street canyons (determined by wind speed and direction, turbulence and boundary layer factors), air tightness of vehicles, vehicle age, type of vehicle and other vehicle characteristics[16,19-25]. However, there is conflicting evidence as to which factors are most important for in-vehicle exposures. It is therefore unclear what the most effective measures are to reduce drivers' exposure.

Pollutant concentrations in heavily trafficked areas depend on street type and vehicle density[22]. In previous studies, intersections and highways have been found to result in the highest in-cabin exposure levels[19,22,26]. Peak hours have also been associated with the highest traffic-related pollution exposure and congestion is thought to be the main contributor to elevated in-vehicle exposure[19]. Further findings support this theory: in-vehicle exposures along high-traffic routes are higher than those experienced on low-traffic routes[27], and high exposures have been found to be higher on weekdays than at weekends[28].

It is not thought that regional meteorology plays a significant part in determining in-vehicle exposures because occupants are protected from the elements[16]. However, micro-meteorology within street canyons could be influential as this can cause high accumulation of pollutants in localised areas[25].

Studies have found that adjusting ventilation settings in vehicles may be the most effective way to reduce drivers' exposure[20,29] . Open windows are thought to lead to higher exposures compared to other ventilation modes, such as outside air and recirculate modes when windows are closed[22,23,29,30]. Another way to reduce in-vehicle exposure is to install filters or air purifiers to the ventilation system[16]. One study found that purifiers reduced ultrafine particle concentrations by up to 99 per cent compared with the outside air[23]. The airtightness of the vehicle cabin is also an important consideration for in-vehicle exposures. A vehicle with a greater air exchange rate has been found to increase in-cabin exposures[16], as this allows ambient pollution to infiltrate into the vehicle cabin more easily. However, there is currently insufficient evidence to confirm whether in-vehicle exposure is substantially affected by different vehicle types and fuel.

Despite a number of studies investigating the determinants of in-vehicle exposures, there is still a significant difficulty in identifying which variables are the most important[16]. Furthermore, most studies investigating determinants and driver exposure do so in controlled experiments, where exposure is measured on a fixed route and the vehicle is driven by a researcher simulating expected commuting behaviour for occupations with a fixed place of work. While these studies can pinpoint slight variations in exposure on a specific route, few studies have measured driver exposures in real-world environments. Consequently, it is uncertain whether these interventions are able to reduce drivers' exposures effectively.

1.3 Professional drivers - an occupation at risk?

While both the intensity of exposures in the commuting environment and the health effects of traffic-related pollution are well established, there have been few studies investigating professional drivers. Typically, office workers may only commute for one or two hours per day. Professional drivers, on the other hand, can spend more than eight hours each shift in this environment.

The majority of professional driver occupational studies to date have measured time-integrated exposure for the duration of a driver's shift (typically between 8 and 16 hours)[31] . While these are useful for epidemiological studies, higher time-resolved exposures can provide specific information on the determinants of exposure and, therefore, suggest more targeted ways in which drivers can reduce diesel exposure. Furthermore, these studies have typically focused on long-haul drivers, with very few studies conducted in urban areas. The earliest study of note on urban professional drivers, in 1996, investigated the differences in $PM_{2.5}$ exposure collected on filters between 10 taxi drivers and office workers in London[32]. The study found higher exposures for taxi drivers compared to office workers who did not use the underground. To our knowledge only seven studies[33-39] have investigated urban professional drivers' exposure to traffic-related pollutants at high time resolutions, with none reported in Europe. The majority of these studies have been performed on a small scale (only Baccarelli *et al)*[33] monitored more than 20 participants) and focused on individual sectors (for example taxi or waste truck drivers). A better understanding of what traffic-related pollutants these drivers are exposed to, in what quantities and what can be done to reduce them is still needed, particularly in the European setting where diesel passenger vehicles make up 42.5 per cent of the total vehicle fleet[40]. Furthermore, professional drivers make up a large proportion of the working population, with 948,133 respondents in the 2011 census being employed in the road transport or mobile machinery sectors in England and Wales. This makes up 3.6 per cent of the working population, making professional drivers one of the largest occupational sectors in the country. This is likely to be an underestimate of the true number, too, as it excludes drivers within the emergency services and other occupations requiring long-distance travel.

Based on the evidence above, one might therefore have expected the long-term consequences of air pollution on this group to have been addressed from a health and safety perspective; yet this has not been done, nor are there any ongoing studies addressing the issue at this time. The urgent need to gather robust data on exposures to professional drivers is also supported by data demonstrating their enhanced personal exposures to diesel exhaust. With the advent of mobile pollutant sensors and GPS trackers, it is now feasible to perform large-scale personal monitoring campaigns that specifically measure diesel exposure in real time. With this degree of temporal and geographical resolution, it is possible to isolate driving behaviours and to identify scenarios that are associated with elevated pollutant exposures.

In the present study, we aimed to fully parameterise these occupational exposures under real-world driving conditions, performing real-time measurements in differing sectors and vehicle types. The additional benefit of this type of personal exposure study is that they also provide an effective platform on which to engage, empower and raise awareness of the occupational air pollution risk within the study population. This study investigates the determinants of professional driver exposure to diesel exhaust and collates information on vehicle specification and driving activities in order to provide potential low-cost mitigation strategies.

2. Project objectives

The overarching aim of the project was to quantify the risk of harm to urban professional drivers of diesel exhaust exposure, allowing the formulation of risk reduction strategies.

This aim was achieved by addressing the following series of objectives:

1. to recruit and assess the exposure to diesel exhaust of 141 professional drivers based in London, both in the working and home environment

2. to characterise driver exposure to inhaled diesel emissions under a range of occupational settings, vehicle types and driving conditions

3. to show the parameters of driver exposures, allowing the dominant variables dictating increased risk of harm from diesel emissions to be identified.

4. to identify and evaluate potential intervention methods for health improvement of a subset of 42 professional drivers, focusing on strategies applicable to the existing vehicle fleet or working practices

5. to develop a database of contextualised driver diesel exposure measurements for future evaluation of mitigation measures.

Due to the absence of applicable previous studies measuring diesel exhaust exposure to professional drivers, the first step in the project was to understand how much, where and when drivers are exposed to high levels of diesel exhaust. By collecting baseline measurements, the characterisation of exposures could be undertaken to identify the most influential determinants of exposure. Following this baseline evaluation, we performed a sub-study examining the use of in-cabin air filters as a means of reducing drivers' exposure.

3. Methods

3.1 Black carbon as a proxy for diesel exhaust

In practice, the precise measurement of diesel exhaust is difficult due to the mix of chemicals which are emitted from the vehicle tailpipe. Commonly, other pollutants are used as a proxy to estimate diesel engine exhaust concentrations in the ambient environment. One of these pollutants is black carbon (BC). Despite not being a regulated air pollutant, it has been employed in this study as the pollutant of measurement for three reasons:

1) It is a pollutant derived from combustion only, has no natural sources (unlike $PM_{2.5}$ or PM_{10}) and, within the urban commuting environment, its major source is diesel engine exhaust[1,22,29]. BC has also been well correlated to other traffic emission indicators such as NO_2, CO and UFP[41-44]. While smoking emissions could also theoretically contribute to BC concentrations, it is illegal to smoke in commercial vehicles and, therefore, the measurement of BC should not affect drivers' measured exposures[45].

2) It has been suggested that BC is one of the most harmful components within ambient particulate matter[44,46]. Due to the size and low density of BC, smaller particulates can remain airborne. These fine and ultrafine particles are thought to pose the greatest risk to health because of their ability to penetrate deep into the lungs when inhaled[47].

3) Technology is available which makes the accurate measurement of BC possible using portable devices[15,18]. The use of personal monitoring devices allows detailed spatio-temporal evaluations of traffic derived pollutant exposures.

Elemental carbon (EC) is typically the most commonly used proxy for measuring diesel exhaust exposure in occupational assessments[48]. It was decided against using EC in this study because it is a filter-based measurement technique and cannot provide high-time resolved measurements. However, BC is an optimal alternative pollutant to measure because both BC and EC are carbonaceous aerosols and primarily differ in measurement method (EC is based on thermal-optical methods while BC uses optical absorption methods)[49]. There is a high correlation between the pollutants, with the latest UK Black Carbon Report (2016) reporting an R^2 between 0.89 to 0.96 across monitoring sites, and measurements being 1.08 to 1.31 times higher when comparing BC to EC[50]. While EC is a common measurement for occupational assessments, there is growing interest in using BC for regulatory air quality assessments, with reports from the World Health Organisation[44], US Environment Protection Agency[51] and European Environment Agency[52] all emphasising the burden this pollutant places on human health[53].

3.2 Fieldwork methods

3.2.1 Sampling equipment

The latest generation microAeth (MA) 300/350[54] was chosen to measure BC. This device measures BC by drawing air through a sampling tube onto a white filter which traps particles in the air. A light beam is then passed through the filter and the change in attenuation is recorded to calculate the concentration of particles. The concentration of BC is determined by measuring the absorbance of particles at a wavelength of 880nm. The device also has an in-built global positioning system (GPS).

Due to the recent development of this device, in 2016, there have been few studies which have used it in exposure studies. However, its predecessor, the microAeth AE51 (Aethlabs), has been used universally for BC personal exposure studies to date[15]. This study used 11 devices: six MA 300s and five MA 350s (**Figure 1**). The devices are essentially the same but the MA350 device casing can withstand outdoor conditions.

Figure 1: Picture of a microAeth 350 (left) and microAeth 300 (right)- 25 September 2019.

3.2.2 Sampling Strategy

Location

London was chosen as the study location, due to its known traffic-related air pollution issues and the large number of professional drivers working within the city[55,56]. London had a total 3 million registered vehicles in 2018[57] and high levels of congestion, with vehicles contributing to approximately 50 per cent of air pollution experienced in the city[55]. While this study aimed to focus on urban drivers within the M25 (the orbital motorway often used to determine London’s geographic boundary), this was not always practical as some drivers had jobs where they were required to drive as far north as Leicester, as far east as Norwich, as south as Brighton and as far west as Bristol.

Participants

Participants were typically recruited in groups of five or ten. An approach was made to a gatekeeper at each organisation to ask professional drivers to participate in the study. To encourage organisations to participate, each organisation was provided with a grey literature report on their drivers' exposures and preliminary recommendations on how they could reduce their exposure at the end of the monitoring. The occupations were targeted to secure a broad range of professional driving sectors. These included taxi drivers; couriers; waste removal, heavy freight and bus drivers; utility services; passenger transport; and emergency services, including fire, police and ambulance. While these sectors were targeted, it wasn't always possible to get equal representation for each sector. Several organisations that were approached declined to participate in the study (**Figure 2**).

Baseline monitoring campaign

The baseline monitoring took place between February 2018 and July 2019, with a total of 146 drivers from 14 organisations being recruited into the study. A summary of the organisations, sectors and participants monitored is provided in **Table 1**. Each participant was asked to carry an MA300 or MA350 unit with them for four days (96 hours, 4 work shifts) whilst at work, commuting and at home. The devices measured BC concentrations at a 10-second resolution. The shifts were primarily day shifts, starting around 6 am and finishing before 6 pm; however, some evening and night shifts were also monitored.

Participants were asked to leave the monitor in their vehicle during their working day. Consequently, it was possible for work exposure measurements to be taken inside a participant's vehicle while the driver had stopped and left the vehicle. This was justified as the study was primarily interested in participants' exposures while driving; it also helped reduce participant burden. At the end of their shift, participants were asked to take the device out of the vehicle and take it home to charge, so that the monitor was operating for the full four days of monitoring. There were times when participants did not charge the devices and, in rare cases, only one out of the four days' monitoring was completed.

Alongside carrying the monitors, participants were also asked to fill in a short questionnaire (**Appendix A**) which detailed their working hours, the type of vehicle they drove, fuel used, the predominant window position for each shift, the predominant ventilation settings for each shift and whether or not they were a smoker. A total 146 participants were provided with monitors. However, five participants had either a faulty instrument or declined to take part after receiving the monitor. Therefore, in total, 141 participants were included in the baseline monitoring analysis.

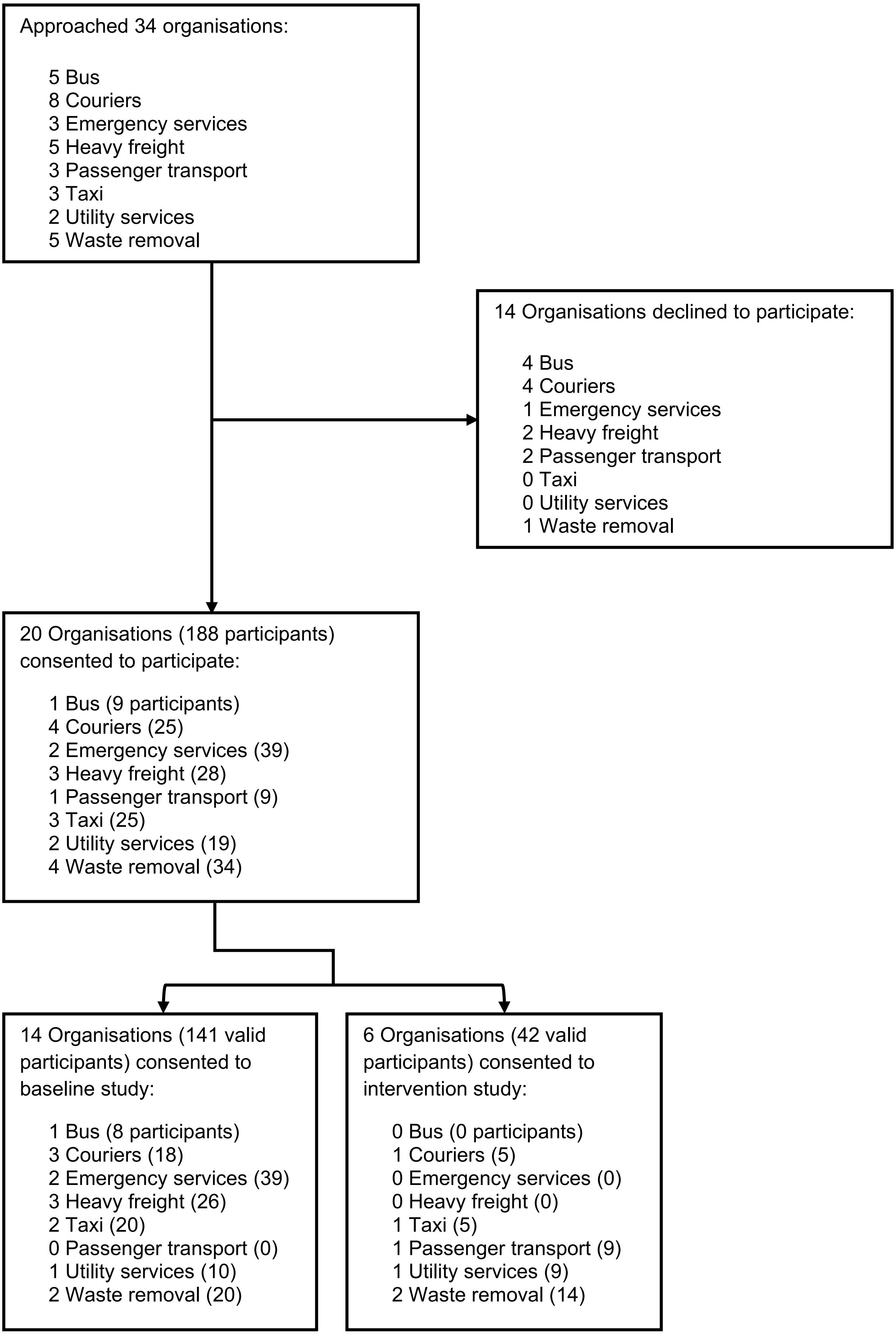

Figure 2: Recruitment flow chart

Intervention Monitoring Campaign

The intervention monitoring campaign was conducted between June and September 2019, involving a total 42 drivers across six organisations (**Table 2**). This monitoring was primarily conducted to assess the efficacy of mobile in-cabin filters. The intervention monitoring campaign largely followed the baseline monitoring with participants asked to monitor over a four-day period. For two of these four days they were asked to have an in-cabin filter operating, while the other two days monitored were without the in-cabin filter. To avoid bias, the participants in the monitoring week were asked to use the in-cabin filter on different days. For example, if ten drivers were monitored during the week, five of the drivers were asked to use the in-cabin filter on days 1 and 2, with five drivers asked to use the in-cabin filter on days 3 and 4. This way, it would reduce the likelihood of drivers only operating the filter on high or low pollution days.

Figure 3: Airbubbl, an in-cabin filter device being used in a vehicle.

The in-cabin filter used in the study was the Airbubbl (**Figure 3**), made by Airlabs (www.airlabs.com). This device uses a fan to draw air through the device and a high-grade particle filter to remove particulates from the air. The product was chosen because, at the time of the study, it was the only known commercially available filter to be specifically used inside vehicles as a retrofit device. The participants were asked to set the device to “boost” mode while driving, which required two presses of the power button until a solid red light was visible.

Table 1: Summary of drivers monitored by sector, participants and shifts for baseline monitoring campaign.

Organisation	**Sector**	**Number of participants**	**Valid participant data**	**Number of shifts monitored**	**Dates of monitoring**	**Shift time**	**Areas of work**	**Generic Vehicle**
Organisation 1	Bus	9	8	28	July 2019	Day	Hatfield to Stevenage, Watford, Edgware and Enfield	Bus
Organisation 2	Courier	5	5	19	October 2018	Day	Predominantly zone 1	Van
Organisation 3	Courier	9	7	18	November 2018	Day	Predominantly zone 1	Electric Van
Organisation 4	Courier	6	6	19	December 2018	Day	Predominantly zone 1	Van
Organisation 5	Emergency Services	19	19	70	April, May, June and August 2018	Day/Night	Zone 1 to 4	Ambulance
Organisation 6	Emergency Services	20	20	64	November and December 2018, January, February, May, June and July 2019	Day/Night	Predominantly zone 1 and 2	Fire Appliance
Organisation 7	Heavy Freight	8	8	32	February 2018	Day	North to Norwich, West to Oxford, South to Brighton and East to Deal	Various Lorries
Organisation 8	Heavy Freight	10	8	31	July and December 2018	Day	Within the M25	Skip Lorry
Organisation 9	Heavy Freight	10	10	36	October 2018	Day	Predominantly within the M25, but sometimes north to Peterborough	Skip Lorry
Organisation 10	Taxi	10	10	34	April and May 2018	Day/Night	Mainly zone 1 and 2 but also out to Heathrow and Gatwick airports	Taxis
Organisation 11	Taxi	10	10	36	May and June 2018	Day/Night	Mainly zone 1 and 2 but also out to Heathrow and City airports	Taxis
Organisation 12	Utility Services	10	10	33	October and November 2018	Day	Within the M25	Small Van
Organisation 13	Waste Removal	10	10	33	April, July and August 2018	Day	Predominantly City of London boundaries	Waste Trucks
Organisation 14	Waste Removal	10	10	34	January and February 2019	Day	Predominantly City of Westminster boundaries	Waste Trucks
		146	**141**	**487**				

Table 2: Summary of drivers monitored by sector, participants and shifts for intervention monitoring campaign.

Organisation	**Sector**	**Number of participants**	**Valid participant data**	**Number of shifts monitored**	**Dates of monitoring**	**Shift time**	**Areas of work**	**Generic Vehicle**
Organisation 1	Courier	5	5	20	June 2019	Day	Predominantly zone 1 and depot located zone 3 West	Courier Van
Organisation 2	Passenger Transport	9	9	30	September 2019	Day	Predominantly zone 1	Passenger vans
Organisation 3	Taxi	5	5	19	September/ October 2019	Day/Night	Mainly zone 1 and 2 but also out to Heathrow and Gatwick airports	Taxis
Organisation 4	Utility Services	9	9	29	July and September 2019	Day/Night	Predominantly zone 1	Van
Organisation 5	Waste Removal	5	5	17	August 2019	Day	Predominantly City of Westminster boundaries	Waste Trucks
Organisation 6	Waste Removal	9	9	30	August 2019	Day/Night	Predominantly zone 1 and depot located zone 3 West	Waste Trucks
		42	**42**	**145**				

3.3 Data processing

3.3.1 Co-location and correction procedure

All devices were co-located periodically during the monitoring period at the London Air Quality Network roadside monitoring station at Marylebone Road (https://www.londonair.org.uk/london/asp/publicdetails.asp?site=MY1). This site was chosen because it experiences a similar pollution environment to the drivers, as the site is 1m from the heavily congested six-lane A501 ring road[58]. Each co-location was run for a minimum of one week. Further details of the co-location process are described in **Appendix B**. The co-locations were averaged over the whole period to use a standardised correction factor over the monitoring campaign (**Table 3**). There was no evidence that different correction factors were required for different seasons or that sensors drifted over time.

Table 3: Correction factors used on each sensor. Correction factors were calculated averaging across all valid co-location campaigns.

Sensor name	Slope	Intercept	R^2
MA300-004	1.19	-0.38	0.83
MA300-005	1.09	-0.17	0.85
MA300-006	1.38	-0.11	0.88
MA300-007	1.20	0.04	0.89
MA300-008	1.10	0.12	0.89
MA300-017	1.16	-0.06	0.72
MA350-001	1.31	-0.03	0.87
MA350-002	1.22	0.05	0.85
MA350-004	1.49	-0.63	0.80
MA350-005	1.39	0.03	0.91
MA350-006	1.10	0.24	0.88

3.3.2 Data cleaning

Data was visualised by participant in order to observe general trends and to flag any unusual data such as wildly fluctuating concentrations or consistently negative values. From discussions with the manufacturer, these signals are consistent with pump issues on the device and, as a consequence, incorrect flow rates being used to calculate BC concentrations. Additionally, isolated one-minute readings that were lower than -20 μg/m^3 were removed from the analysis, as this was likely to be due to the device being knocked while being carried, resulting in the light absorption measuring on a clean part of the filter before realigning to the loaded filter spot. Small negative values were kept in the analysis as this is often typical with MicroAeth measurements, where small negatives are offset by small positives in the following observation[59]. In total, 9 per cent of data collected were not considered for further analysis.

3.3.3 Global Positioning System and coordinates processing

The GPS data collected was employed to determine the type of activity each participant was undertaking. This technique has been demonstrated in a number of papers previously[60-64]. GPS coordinates were used in this study to determine whether the participant was moving or stationary. Further details on the GPS process to stratify moving points are described in **Appendix C**.

3.3.4 Data analysis

Data were downloaded using 'MicroAeth Manager' software from Aethlabs and then parsed into the database using SQL software. Correction factors calculated in **section 3.3.1** were then applied to the data in SQL. Questionnaire data were populated in a separate meta table and joined to corresponding participants' BC data.

After data processing, each participant's data set comprised of one-minute resolution BC concentrations, date and time, GPS coordinates, speed, average speed for the last 15 minutes, bearing and average bearing for the last 15 minutes. Each one-minute point was labelled whether the participant was at work or not, what shift the participant was on, predominant ventilation setting for the shift, predominant window position for the shift, the vehicle the participant was driving and if the participant was moving or stopped from GPS stratification. Activities were labelled as follows: '*At work driving' (*during work hours and moving); '*At work not driving'* (during work hours and stopped); '*Commuting'* (outside of work hours and moving); and '*At home' (*outside of work hours and stopped).

Data were summarised by participant- for each participant's total monitoring period and on a per shift basis for work exposures. Statistical tests were performed in 'R statistics'[65]. Due to non-normality (normality tested using the Shapiro-Wilk test) of data, Kruskall Wallis H tests were run to assess differences between sectors. *Post hoc* tests were run using pairwise Dunns tests and 'Holm' adjustment.

3.3.5 Analysing determinants affecting driver exposure

To analyse determinants affecting exposure, the one-minute dataset was averaged up to 15 minutes, as this resolution would allow exposure measurements to be paired to reference London background concentrations of BC. Background concentrations are thought to be an important explanatory variable for personal exposures[66].

London background concentrations of BC were obtained from the aethalometer at the North Kensington urban background site as it was operational for the entire monitoring period. There were some missing values, where the background monitor was not operating. If there were background data available within three hours of exposure data, these were filled to the closest time period. For measurements outside of three hours, these background readings were left blank.

Meteorological variables were taken using the "worldmet" package[67] in R including temperature, relative humidity, wind speed, wind direction and precipitation from St James's

Park and Heathrow Airport weather stations. Temperature and relative humidity were taken from the St James's Park site as it was decided this would better reflect the temperature in central London, where most of the drivers were located. This station did not have regular wind speed, wind direction and precipitation measurements, so these data were taken from the Heathrow Airport station. Each meteorological variable was available hourly and was forward filled to the 15-minute dataset (ie meteorological data at 15:00 was filled for exposure data times at 15:00, 15:15, 15:30 and 15:45).

Other determinants included in the analysis were: predominant ventilation settings for the shift, predominant window position for the shift; generic vehicle type (ie van, truck, taxi etc); vehicle speed; day of week; hour of day; weekday or weekend; season; sector; company; fuel type; make and model of vehicle; whether it was a school holiday; whether the participant was a smoker; the location of driver by borough; and the location of driver in London (central, inner, outer or outside London, as defined by the Office for National Statistics)[68] All these determinants were used to identify the cause of high exposure for drivers, both individually and in mixed effects models.

Factors were first analysed individually, with both absolute measured BC and also following adjustment for the background concentration in BC measured at North Kensington. This adjustment removes the diurnal variation in ambient BC. Kruskall Wallis H tests were run to assess the differences between determinants of exposure. *Post hoc* tests were run using pairwise Dunns tests, using 'Holm' adjustment.

Due to the lack of independence of the exposure dataset (ie exposure at time *n* is dependent on exposure at time *n*-1), mixed effects models were run to best identify the determinants of driver exposure at 15-minute exposure resolution. These models were adjusted for the random effect of each participant and assessed fixed effects of all other determinants. The mixed effects models were run in 'R Statistics'[65] using the 'lmerTest' package[69]. Analysis of models was completed by running a full model (ie model with all determinants) and generating all combinations of all fixed effects. The optimal model was chosen as the model with the lowest corrected Aikaike information criterion (AICc). This is a measure of the most efficient model fit (ie a balance between underfitting and overfitting of the model). This analysis was run using the 'dredge' function in the 'MuMIn' package[70]. Despite the residuals violating the normality assumption, data were not logged transformed for the mixed effect models. If datasets are sufficiently large, as is the case in this study, previous studies have found that linear regression models outputs are robust to non-normal residuals[71]. The benefit of using unadjusted data are that the outputs provide an absolute exposure effect for each determinant, which cannot be calculated when using transformed data.

The intervention study analysis was carried out in the same way as the determinants analysis, except exposures were assessed on a shift basis, because the primary aim of this analysis was to assess the effectiveness of in-cabin filters in reducing drivers' exposures over an entire shift. The intervention data were also analysed through mixed effects models.

The mixed effects models are presented as:

$$(bc\ driving)_{ij} = \alpha + (participant)_i + \beta_n(fixed\ effect)_{ij} + \ldots + \varepsilon_{ij}$$

Where i is the index of each participant and j is the index of the 15-minute or shift 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 βs are the fixed effects of each variable and ε_{ij} is the residual.

4. Results

4.1 Overview of exposures

4.1.1 Activity exposure

A total 141 participants were analysed for the baseline monitoring campaign. However, there were several participants who did not capture data for the full 96 hours, due to the monitor malfunctioning or battery failure. Participants were only included if they had a minimum of one full shift of data. In total, 11,492 hours of professional driver exposure data were analysed.

Summary statistics for all exposures monitored are presented in **Table 4**. The average overall exposure for participants was 2.0 ± 1.4 μg/m^3. '*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) ($p < 0.01$). The standard deviations were often higher than mean exposures, indicating a large variability and, at times, very high levels of BC exposures experienced by participants. When activities were split into '*driving*' and '*not driving'* activities, average exposures highlighted further differences. '*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). '*Commuting*' exposures were also comparatively high (3.6 ± 2.5 μg/m^3). However, as participants did not spend a substantial proportion of time in this environment (typically less than an hour each day), the contribution to total BC exposure of participants was low. There was a significant difference in average exposures 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 ($p=0.54$).

Table 4: Summary statistics by participant for mean, standard division, minimum, median and maximum BC exposures across different activities.

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

*SD = is presented as the arithmetic standard deviation between participants

There was a substantial range of exposures between participants. The highest average *'at work'* exposure was a waste removal driver at 32.6 μg/m^3, while the lowest was an emergency service worker at 0.5 μg/m^3. Furthermore, there was a wide range of exposures experienced by individual participants, both within and between different activities, highlighting the complexity of characterising exposures within this population. '*At work driving'* exposures had the largest range between participants, with the lowest exposed participant experiencing an average exposure of 0.8 μg/m^3 and the highest exposed participant experiencing an 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).

4.1.2 Time-weighted exposure

Six participants' monitors did not have GPS readings and driving exposures could not therefore be determined. Additionally, 13 participants did not take their monitors home with them so *'at home'* exposures could not be analysed. For comparability, only 122 of the of 141 participants were analysed in the time-weighted exposure analysis.

Figure 4 illustrates the time-weighted exposures of participants. On average, 18.6 per cent of time was spent by the participants *'at work driving'* but this contributed 36.1 per cent of total BC exposure. 54.4 per cent of time was spent *'at home'* but this only contributed 31.8 per cent of total BC exposure. Average *'commuting'* exposures were relatively high but with only 4.0 per cent of time spent in this activity, it only contributed 7.9 per cent to the total exposure. Average *'at work not driving'* proportions were relatively similar for BC exposure (24.2 per cent) and time spent (23.0 per cent), indicating the comparatively lower exposures experienced during this activity compared to *'at work driving'*. These results highlight that over 60 per cent of BC exposures for these participants can be attributed to work activities, despite spending only 42 per cent of their time at work. The box plot also confirms the large variability in exposures and the time spent undertaking each activity between participants. Unsurprisingly, the more time that participants spent driving, compared to other activities, the greater the increase in BC exposure.

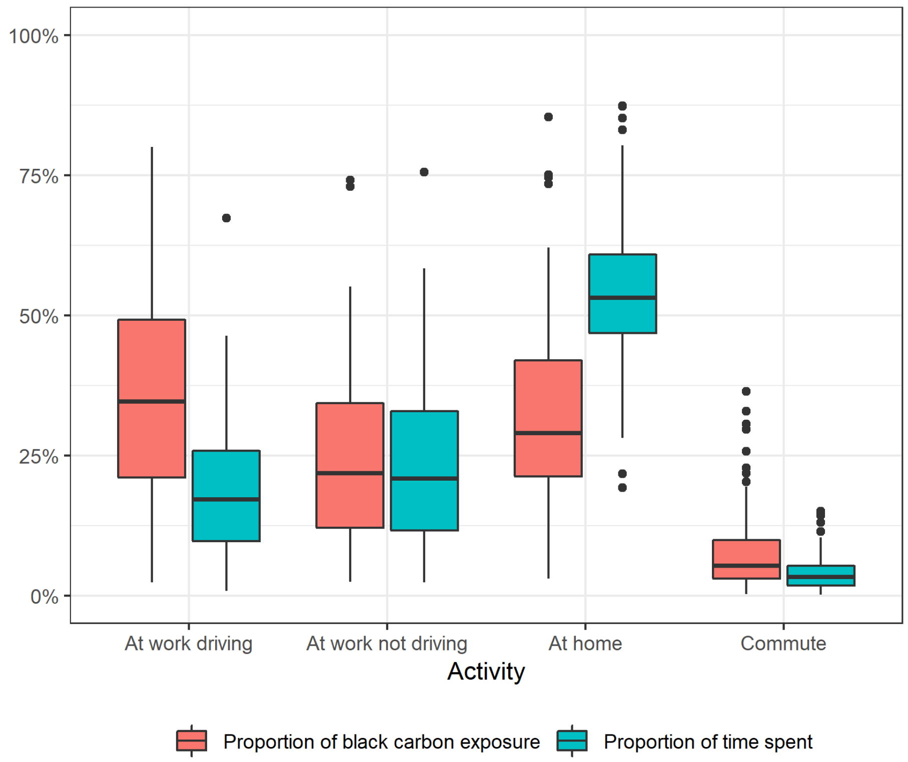

Figure 4: Box plot of the proportion of BC exposure and the proportion of time spent in each activity for participants.

4.1.3 Comparison to fixed monitors

The comparison of *'at work driving'* exposure (4.2 ± 4.7 µg/m^3) to fixed monitors across the monitoring period found that average driver exposure was approximately a third higher compared to the Marylebone Road roadside monitoring site (3.1 ± 2.1 µg/m^3) and four times higher than the background monitoring site at North Kensington (0.9 ± 0.8 µg/m^3). The variation and magnitude of exposures recorded at Marylebone Road did not reflect the significant variability in exposures experienced by drivers, reiterating the need for personal exposure studies to better reflect the driving population's exposure. Despite this, the average exposures for all times '*at work*' of 3.1 ± 3.5 µg/m^3 were comparable to measured BC concentrations at Marylebone Road. Again, these do not reflect the variation in individual exposures.

4.2 Differences between sector exposures

This section details a general characterisation of shift exposures observed across different professional driving sectors. A more detailed analysis, adjusting for confounding variables using mixed effects models, is presented later in the report in **section 4.4**.

Table 5 presents a summary of different exposures experienced across the different professional driving sectors. Taxi drivers exhibited the highest exposures of all the sectors monitored, while the emergency services exhibited the lowest. There was a significant difference between exposures across the various sectors for all times *'at work'* ($p < 0.01$), with *post hoc* test results summarised in **Appendix D**. The trend in average *'at work'* exposures largely followed the highest *'at work driving'* exposures, except for the emergency service workers and bus drivers. Emergency service exposure while driving was slightly higher at 2.8 ±

1.4 μg/m^3 compared to bus drivers at 2.3 ± 0.8 μg/m^3. However, due to the comparatively short time spent driving by emergency services (around 2 hours per shift), the overall average exposure was lower, with bus drivers spending 5.5 hours of their shift driving. Taxi drivers spent the most time of their shift driving (6.5 hours) and had the highest *'driving'* exposure, 6.6 ± 4.9 μg/m^3, reflecting the highest *'at work'* exposures of all occupations. Heavy freight drivers spent the second longest time driving (6.1 hours), yet only had the fourth highest average exposure of all the sectors, potentially indicating differences in driving characteristics for this occupation.

There was a significant difference between sector exposures for *'at work driving'* ($p < 0.01$). The *post hoc* pairwise tests found significant differences between all sectors and taxi drivers (**Appendix D**). Potential explanations for the differences in exposures observed between sectors were that taxi drivers spent most of their time in central London, dropping and picking up passengers in congested areas and thus leading to higher driving exposures. Heavy freight drivers often drove long distances on highways, far outside of London and in free-flowing traffic, possibly explaining their lower average exposures. Couriers were also largely concentrated in central London; however, they were not required to drive in such heavily congested areas as they spent periods dropping off goods in loadings bays and, therefore, experienced lower driving exposures than taxi drivers. Driving exposures for waste removal drivers were not significantly different when compared to all other sectors (**Appendix D**), possibly due to the wide range of exposures they experienced, with shift exposure ranging from 1.0 to 51.9 μg/m^3. The low exposures experienced by emergency services likely reflects their capacity to by-pass congestion when attending an incident, reducing the possibility of pollutants infiltrating the vehicle cabin. Bus driver exposures were only measured on the outskirts of London, in the less congested Hatfield and Stevenage areas. These routes on the periphery of London could potentially explain the low exposures experienced by these drivers. Utility service drivers drove small vans in London suburbs; therefore, the location and vehicle type could explain the comparatively low exposures experienced by these drivers.

There was a significant difference between sector exposures for *'at work not driving'* ($p < 0.01$, *post hoc* testing between groups are shown in **Appendix D**). Comparatively high taxi, courier and waste removal exposures can be explained by the fact that stops often occurred in central London. Low exposures experienced by emergency services, bus and utility services drivers indicated that the '*not driving*' exposures often occurred in indoor locations. For utility services and emergency services, these stops were for long periods, averaging 6.4 and 8.8 hours per shift respectively.

While there was a large variation in exposures between sectors, '*driving*' exposures still had an impact on overall exposure (

Table 6). Despite sectors only spending between 9 per cent and 27 per cent of time driving, this contributed between 17 per cent and 51 per cent of total BC exposures and was the highest proportion of exposure in five of the seven sectors monitored. Emergency services had a higher proportion for *'at work not driving'* and couriers had a higher proportion *'at home'*.

Table 5: 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 (standard deviation) BC exposure (µg/m³)				Mean (standard deviation) 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)**

Table 6: Summary of average proportion of BC exposure and average proportion of time spent for each sector across different activities.

	At work driving		**At work not driving**		**At home**		**Commute**	
Sector	Percentage of BC exposure	Percentage of time spent	Percentage of BC exposure	Percentage of time spent	Percentage of BC exposure	Percentage of time spent	Percentage of BC exposure	Percentage of time spent
Taxi	47.8	21.0	9.4	7.9	33.5	66.5	9.8	4.8
Courier	29.3	14.9	24.8	22.2	38.5	59.2	7.4	3.7
Waste Removal	41.4	25.0	23.7	15.7	29.1	54.9	6.2	4.6
Heavy Freight	50.9	27.1	18.2	17.1	23.8	51.9	7.2	3.9
Utility Services	40.7	17.4	38.5	39.3	19.1	42.7	2.6	0.9
Bus	46.0	26.0	14.3	15.0	31.6	54.3	8.1	4.6
Emergency Services	17.0	8.9	38.0	39.3	36.5	48.3	9.0	3.7

4.3 Characterising exposure

4.3.1 Diurnal and activity exposure characteristics

Visualising exposures over time can provide important information on the characteristics and cause of high exposures experienced by professional drivers. Individual BC exposures were shown 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. To highlight the differences and similarities observed between individuals and sectors, examples of different participants' exposure over 24 hours is presented in **Figure 5**.

These time series present an example of a taxi driver who spent most of a shift driving, with high spikes in exposure occurring when *'at work driving'*. The second example shows an emergency services worker whose highest exposure during the day occurred while they were *'commuting'* by tube. This participant rarely drove during their shift but when they did this also resulted in elevated BC exposures. Another time series graph presents exposures of a bus driver who experienced comparatively low exposures for their entire shift but also had small elevated levels when *'at work driving'*. The final example highlights a large exposure spike experienced by a heavy freight driver while *'at home'*, likely caused by heating or cooking activities indoors. This participant also experienced elevated exposures when *'commuting'* and *'at work driving'*.

These time series graphs show that, despite all being professional drivers, there are vast differences in activities and exposures experienced. However, a recurring theme in the characteristics of diurnal exposure for participants was that elevated exposures were all experienced when *'at work driving'*.

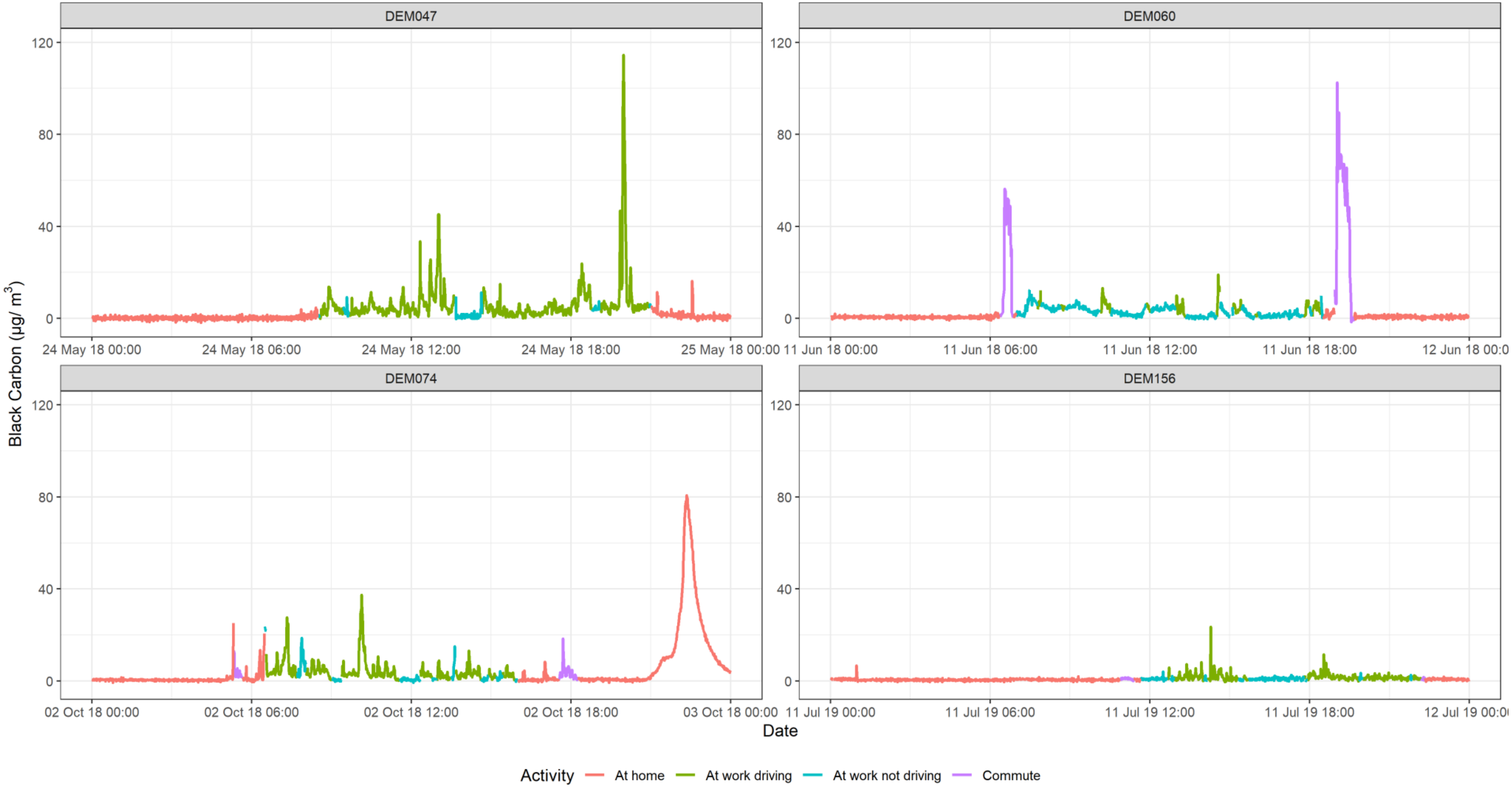

Figure 5: Examples of 24-hour exposures for a selection of participants (clockwise from top left) from taxi, emergency services, bus and heavy freight sectors.

4.3.2 Spikes in black carbon exposure while driving

Analysis showed *'at work driving'* was highly influential on overall exposure, with multiple spikes in BC evident. Visualising these spikes spatially can assist with understanding the likely cause of the high exposures experienced by these drivers. **Figure 6** shows a selection of high exposure events experienced by three participants while driving. Increases in exposure while driving were rapid and remained entrapped within the vehicle cabin for 10 minutes to an hour, before returning to pre-spike levels. There were also times where BC levels slowly accumulated or spiked on multiple occasions over a short time period. The fact that pollutants are 'transported' while driving may partially obscure the determinants of high exposure, particularly as the location of the highest exposure can be many minutes after the cause of the increase. From these observations 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 of determining the causes of high exposures while driving.

Further examples of high exposure events are presented to illustrate some other determinants of high exposures experienced by the drivers. **Figure 7** and **Figure 8** show that tunnels can cause a localised accumulation of air pollution which infiltrates into the cabin when vehicles pass through. In these examples, multiple instances are presented where participants were travelling through the Blackwall and Rotherhithe tunnels which caused an increase of drivers' BC exposures of up to 80 $\mu g/m^3$. Furthermore, once exiting the tunnels, this increase in exposure was observed to remain within the cabin for up to 20 minutes.

Figure 9 shows an example of a long duration spike, where pollution infiltrated the vehicle cabin at Barnet Hospital. This spike was possibly due to idling or cold-start vehicles around the hospital car park. This spike lasted 75 minutes after the initial increase, again showing that these elevated exposures can be sustained in the vehicle cabin for long periods.

Figure 10 again shows the influence of congestion on driver exposure along Marylebone Road. However, in this example the increased exposure levels rapidly dissipate after leaving the congested area, possibly suggesting that exposures can be reduced if drivers can avoid highly congested areas.

All these examples present qualitative evidence on some of the causes of high BC exposures for drivers. This type of analysis is useful alongside quantitative analysis as it illustrates the cause of exposure and may also isolate incidences of high exposure that may be difficult to identify in statistical analysis (such as the impact of spikes in exposure). Nevertheless, a full quantitative analysis is still required on the factors affecting drivers' exposures as confounding or complimentary determinants can be adjusted for in statistical analysis. An example of this is the effect of congestion on drivers' exposure when the driver has their windows open or closed.

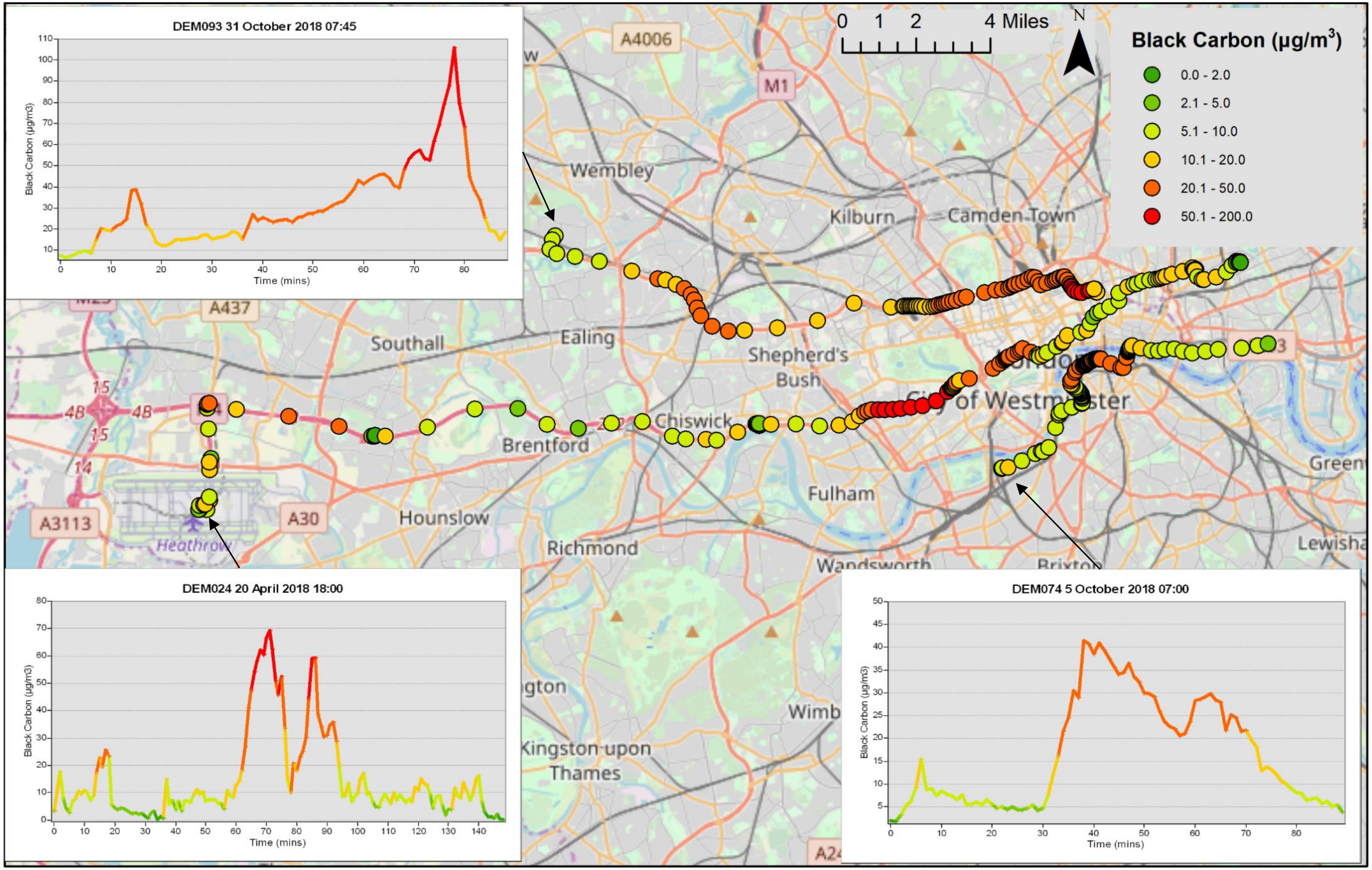

Figure 6: Examples of high exposure events from a selection of participants while driving from west to east across London (clockwise from top left) from courier, heavy freight and taxi sectors. Arrows point to the starting position of each graph and titles indicate the starting time of each event. Each dot represents one-minute of exposure.

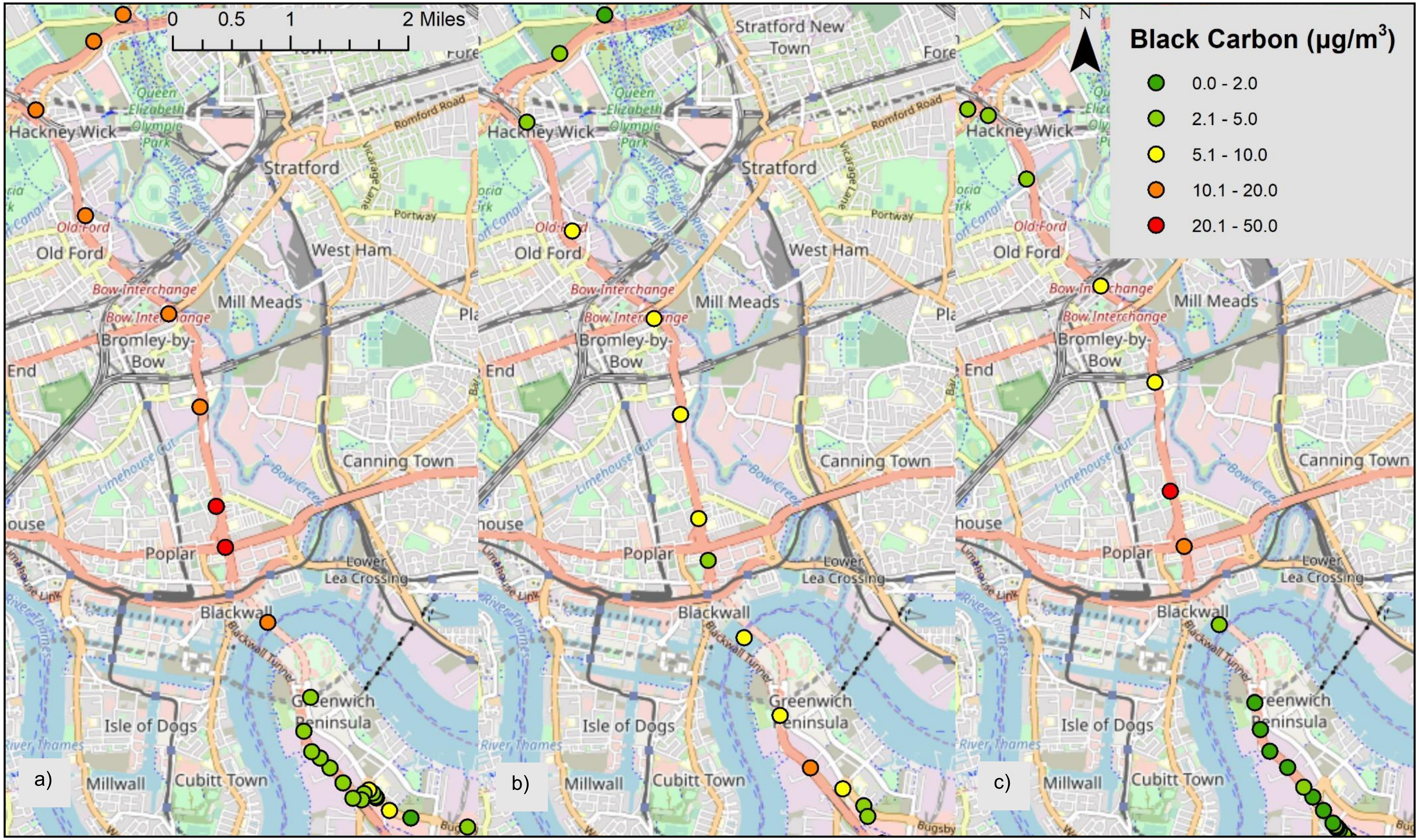

Figure 7: High BC exposure events travelling through the Blackwall Tunnel by a heavy freight driver (DEM013). a) South to north at 08:00 on 14 February 2018; b) North to south at 09:00 on 14 February 2018; c) South to north at 09:00 on 15 February 2018. Each dot represents one-minute of exposure.

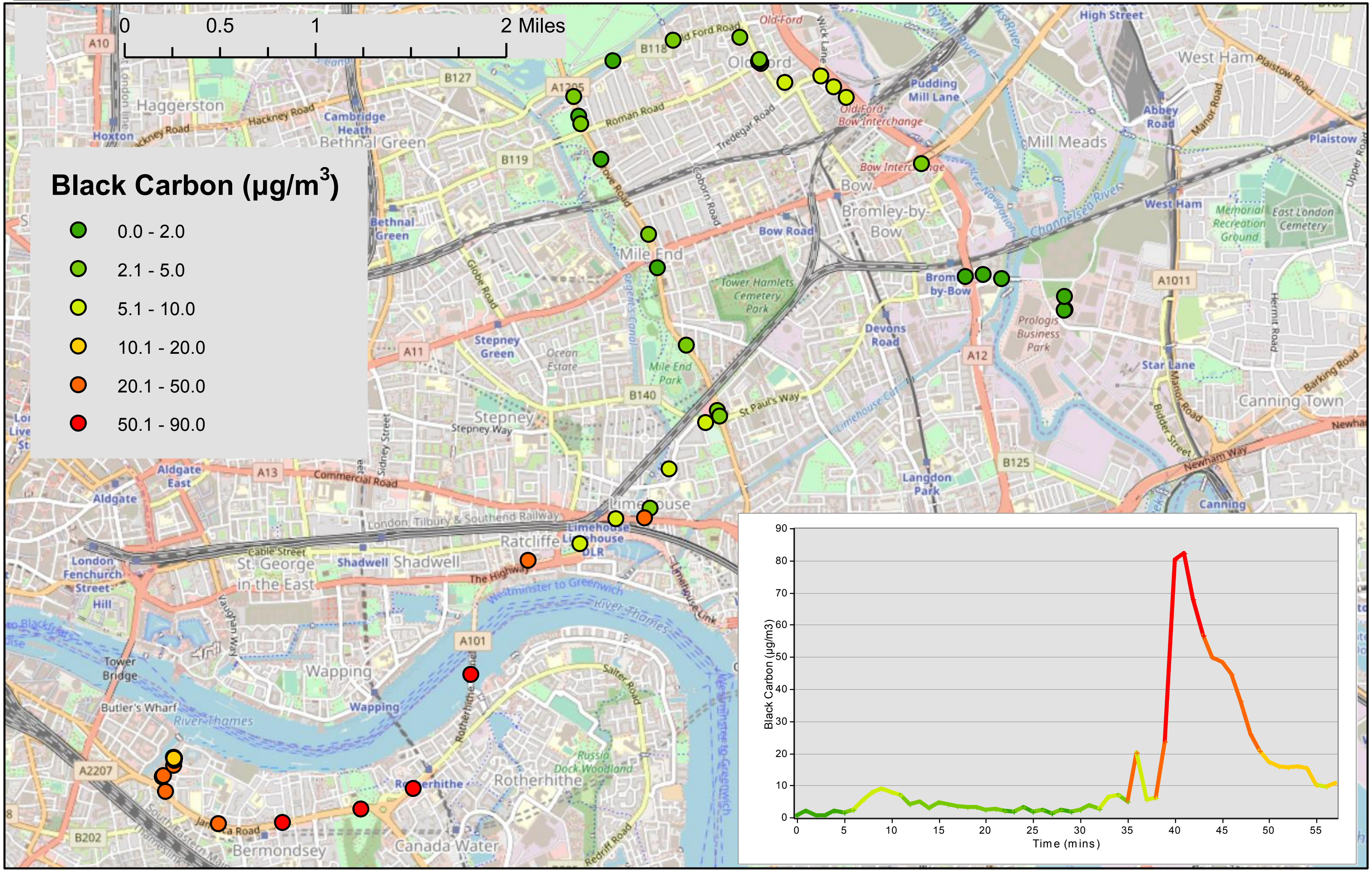

Figure 8: Example of a courier driver's (DEM098) BC exposure driving from Bow (East) to Bermondsey (South) through Rotherhithe Tunnel starting at 08:30, 8 November 2018. Each dot represents one-minute of exposure.

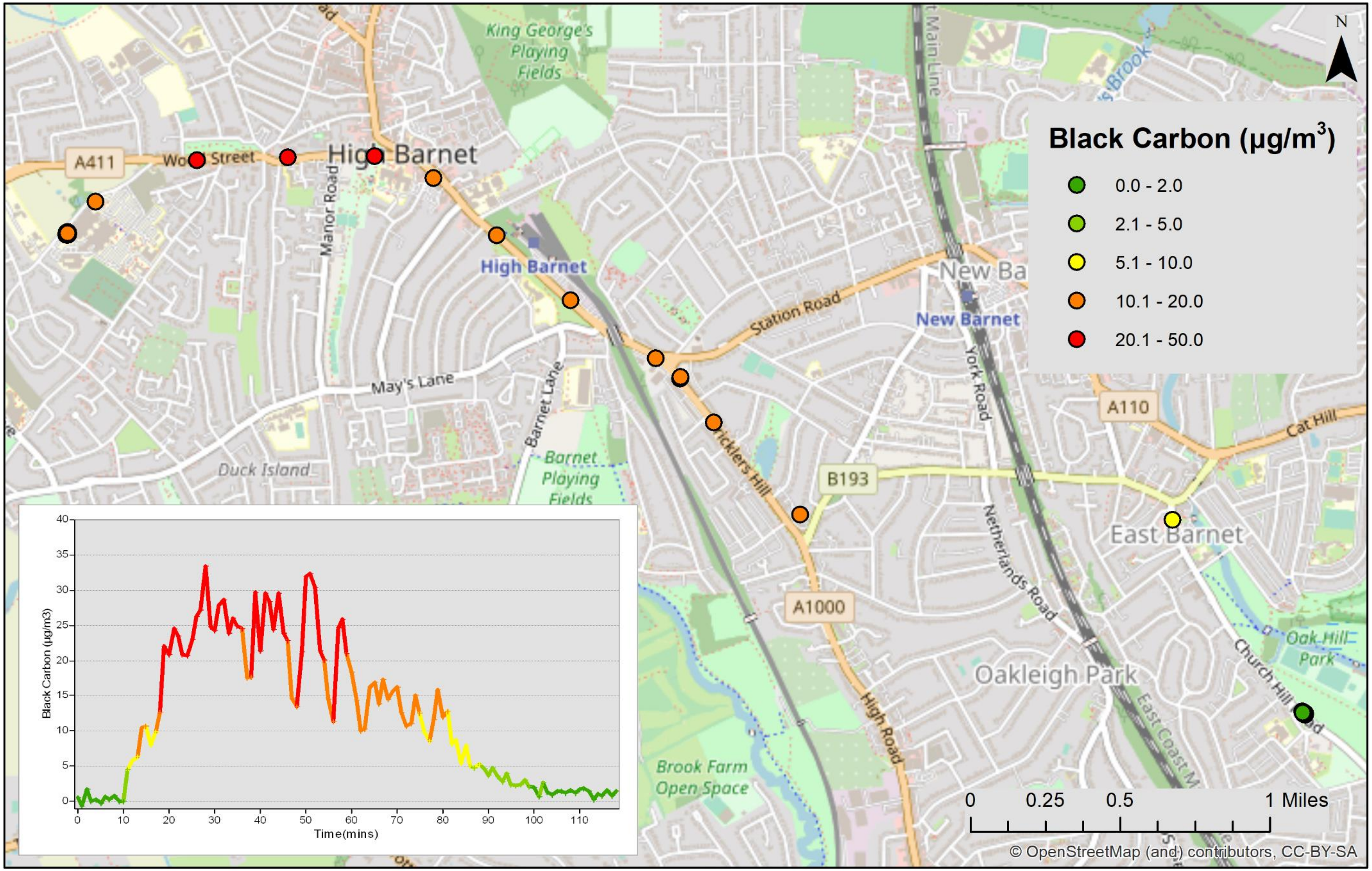

Figure 9: Example of an emergency service driver's (DEM041) BC exposure driving from Barnet Hospital (west) to Churchill Hill Road (east) starting at 8:15, 11 May 2018. Each dot represents one-minute of exposure.

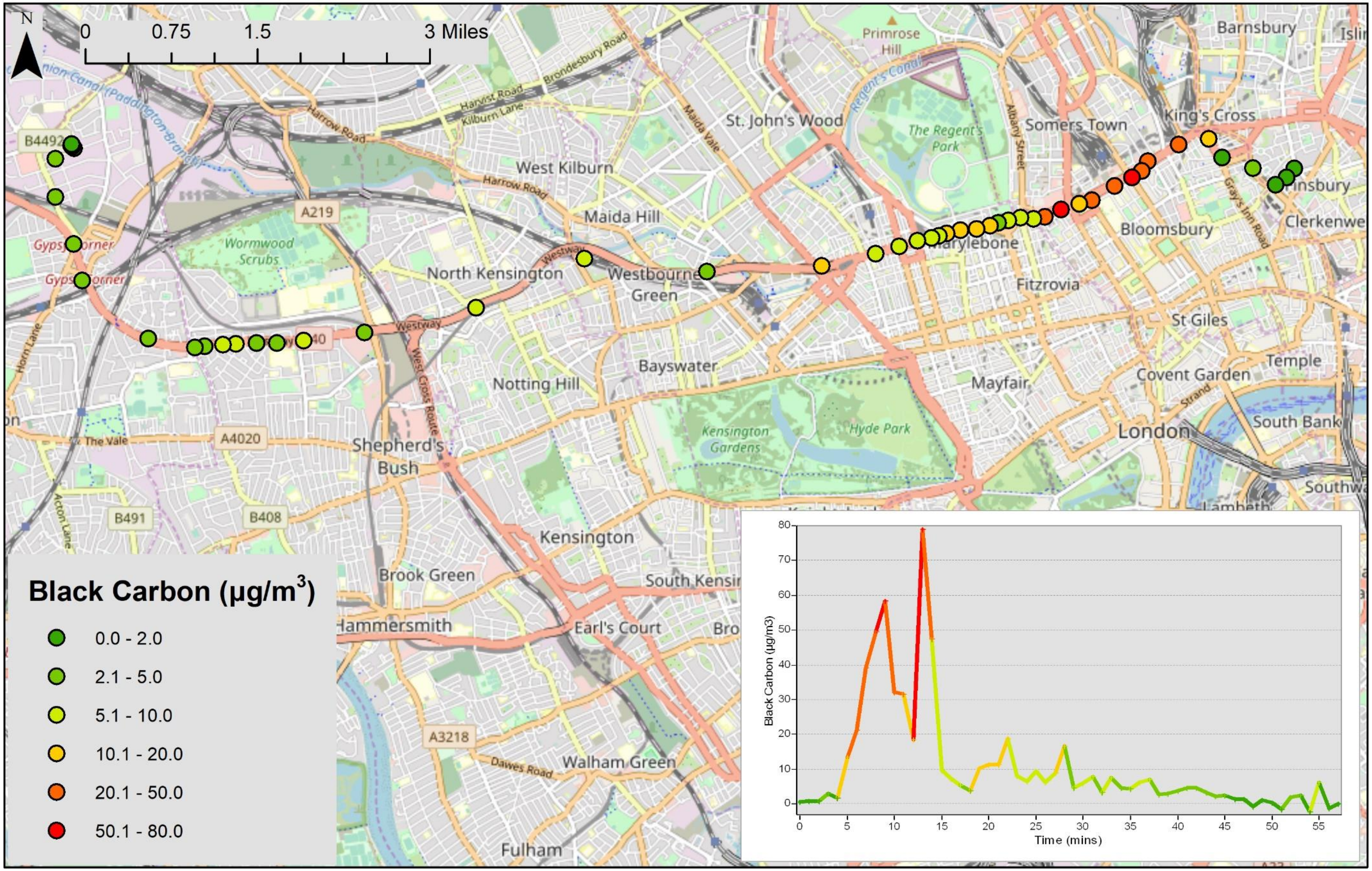

Figure 10: Example of a waste removal driver's (DEM189) BC exposure driving from King's Cross (East) to Acton (West) through congestion on Marylebone Road starting at 12:00, 23 August 2019. Each dot represents one-minute of exposure.

4.4 Statistical analysis of determinants affecting drivers' exposures

This section describes a detailed statistical analysis of all determinants affecting *'at work driving'* exposures. First, categorical factors for exposures were analysed individually. These were assessed for both absolute BC exposure and adjusted BC exposure, which subtracts background BC from the absolute values. The adjustment of background BC allowed diurnal and temporal patterns in ambient BC concentrations to be removed. Without this adjustment, results on the influence of certain driving-based determinants could have been misinterpreted, as background levels have previously been identified as a key explanatory variable for personal exposures[66].

Data were analysed at a 15-minute resolution, so the spikes in BC exposure discussed in the previous section were not diluted, as would be the case if average shift exposures were used. Use of this higher resolution could also provide time-specific recommendations in reducing exposure for drivers. Investigation of the relationship between exposure and continuous variables, such as vehicle speed, could not be easily completed without controlling for confounding variables. Therefore these factors are only discussed in the mixed effects model. The mixed effects model was adjusted for any interaction between determinants, so that the most influential factors on *'at work driving'* exposures could be identified.

4.4.1 Window position and ventilation settings

The predominant window position for a shift had a significant influence on exposure, with average exposure being 4.8 ± 7.5 μg/m^3 with windows open compared to windows closed at 3.7 ± 6.1 μg/m^3 ($p<0.05$). Values adjusted for background BC levels also showed similar trends (**Table 7**). This finding was in line with other studies which have suggested that having windows open resulted in an increase in drivers' exposure[23,29]. The lower median values in comparison with the means exhibited the influence of a non-normal distribution of exposure and occurrences of very high exposures. *Post hoc* tests on all determinants are presented in **Appendix E**.

Ventilation settings were only assessed for vehicles with windows closed as these settings would have very little influence on exposure when windows were open. For absolute exposures, the recirculate setting (as the predominant setting for a shift) had significantly lower levels ($p<0.05$) compared to off and outside air mode (**Table 8**). When values were adjusted for background concentrations there appeared to be a slightly higher level for drivers who had their settings set to off compared to other modes.

Table 7: Effect of predominant window position for shift on *'at work driving'* exposures. SD refers to standard deviation.

		BC exposure (μg/m³) *		Adjusted BC exposure (μg/m³) *	
	Time (hours)	Mean (SD)	Median	Mean (SD)	Median
Windows Open	1163	4.7 (5.8) [a]	3.2	4.0 (6.1) [a]	2.5
Windows Closed	740	3.6 (5.0)	2.4	2.7 (5.0)	1.6
Not reported	4	2.6 (0.9)	2.7	1.1 (1.2)	1.1

* Kruskal-Wallis test shows a significant difference in driver BC exposure ($p<0.001$) and adjusted BC exposure ($p<0.001$) between different window position categories.

'a' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure ($p<0.001$) and adjusted BC exposure ($p<0.001$) between windows open and windows closed

Table 8: Effect of predominant ventilation settings for shift on *'at work driving'* exposures for times when windows are closed. SD refers to standard deviation.

		BC exposure (μg/m³) *		Adjusted BC exposure (μg/m³) *	
	Time (hours)	Mean (SD)	Median	Mean (SD)	Median
Off	106	3.8 (3.7) [a]	2.7	2.9 (3.7) [a]	1.8
Outside Air	280	3.7 (3.4) [b]	2.8	2.6 (3.4) [b]	1.9
Recirculate	328	3.0 (3.1)	2.1	2.2 (3.1)	1.4
Not reported	26	8.9 (19.7)	1.7	12.4 (24.0)	1.3

* Kruskal-Wallis test shows a significant difference in driver BC exposure ($p<0.001$) and adjusted BC exposure ($p<0.001$) between different ventilation settings.

'a' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure ($p<0.001$) and adjusted BC exposure ($p<0.001$) between off and recirculate ventilation settings.

'b' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure ($p<0.001$) and adjusted BC exposure ($p<0.001$) between outside air and recirculate ventilation settings.

4.4.2 Smoking status

Drivers were asked if they were smokers in order to observe the effect of smoking on exposure. Being a smoker showed significantly higher exposures while driving (**Table 9**) ($p<0.05$). It is thought that this was not directly related to smoking as it is illegal to smoke in a commercial use vehicle[45]. Furthermore, previous research has demonstrated that BC smoking profiles are distinctive compared to other pollution sources, with extremely high peaks greater than 150 μg/m³ lasting for less than five minutes[72]. Such exposure profiles were not observed while driving in this study. The differences in exposure for drivers could instead relate to personal characteristics of smokers. For example, 94 per cent of smokers drove with their windows open (compared to only 48 per cent of non-smokers) and 52 per cent were heavy freight drivers. Another possible explanation of higher exposure was that smoking breaks were taken closer to vehicles which could have resulted in tobacco emissions filtering into the cabin.

Table 9: Effect of smoker status on *'at work driving'* exposures. SD refers to standard deviation.

	Time (hours)	BC exposure (µg/m^3) * Mean (SD)	Median	Adjusted BC exposure (µg/m^3) * Mean (SD)	Median
Non-smoker	1478	3.9 (4.6) [a]	2.7	3.1 (4.7) [a]	1.9
Smoker	337	5.1 (5.8)	3.6	4.4 (6.1)	2.9
Not reported	92	6.9 (12.9)	3.4	5.6 (12.1)	2.1

* Kruskal-Wallis test shows a significant difference in driver BC exposure (p<0.001) and adjusted BC exposure (p<0.001) between different smoker status categories.

'a' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure (p<0.001) and adjusted BC exposure (p<0.001) between smokers and non-smokers.

4.4.3 Day of week

Our analysis did not find any difference between weekend and weekday driving (p=0.56) (**Table 10**). It was hypothesised that exposure would be lower due to the reduced number of vehicles on the road during the weekend, particularly in central London areas[73]. However, there was a substantially smaller number of drivers working at the weekend, which could also skew data and explain why this study did not observe a significant difference in drivers' exposures between weekend and weekdays.

Table 10: Effect of day of week on *'at work driving'* exposures. SD refers to standard deviation.

	Time (hours)	BC exposure (µg/m^3) Mean (SD)	Median	Adjusted BC exposure (µg/m^3) Mean (SD)	Median
Weekday	1750	4.3 (5.7)	2.9	3.5 (5.9)	2.1
Weekend	157	3.9 (3.5)	3.0	3.0 (3.5)	2.2

4.4.4 Time of day and season

Time was split into four categories: 'morning peak' between 7 am and 10 am; 'day' from 10 am to 4 pm; 'evening peak' between 4 pm and 7 pm; and 'night' from 7 pm to 7 am. There was a significant difference between all time periods (p<0.05, **Appendix E**) except morning peak and night exposures. The afternoon peak had the highest exposure, followed by night exposures (**Table 11**). Surprisingly, the morning peak was the lowest exposure time period after adjusting for background BC. This finding was largely in line with diurnal patterns in background levels; however, ambient night concentrations are typically much lower compared to other times of day[50].

There were statistically significant differences between all seasons (**Table 12**) (p<0.05, **Appendix E**), with the highest exposures measured in spring, followed by autumn, with no difference between summer and winter exposures. Caution should be exercised when interpreting this result as monitoring for different sectors was often completed within a season and therefore this difference could be caused by sector characteristics and not the difference between seasons. This confounder will be adjusted for in the mixed effects model to better identify the seasonal influence on driving exposures.

Table 11: Effect of time of day on *'at work driving'* exposures. SD refers to standard deviation.

		BC exposure (μg/m^3) *		Adjusted BC exposure (μg/m^3) *	
	Time (hours)	Mean (SD)	Median	Mean (SD)	Median
Morning peak	375	4.3 (4.5) [a,b]	3.1	3.1 (4.6) [a,b]	1.8
Day	1031	4.0 (5.1) [c,d]	2.7	3.3 (5.2) [c]	2.1
Afternoon peak	203	5.2 (7.3) [e]	3.1	4.6 (7.7) [e]	2.6
Night	298	4.6 (6.7)	3.0	3.7 (6.8)	2.0

* Kruskal-Wallis test shows a significant difference in driver BC exposure (p<0.001) and adjusted BC exposure (p<0.001) between different times of day.

'a' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure (p<0.001) and adjusted BC exposure (p<0.05) between morning peak and day.

'b' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure (p<0.01) and adjusted BC exposure (p<0.001) between morning peak and afternoon peak.

'c' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure (p<0.001) and adjusted BC exposure (p<0.001) between day and afternoon peak.

'd' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure (p<0.01) between day and night.

'e' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure (p<0.001) and adjusted BC exposure (p<0.001) between afternoon peak and night.

Table 12: Effect of season on *'at work driving'* exposures. SD refers to standard deviation.

		BC exposure (μg/m^3) *		Adjusted BC exposure (μg/m^3) *	
	Time (hours)	Mean (SD)	Median	Mean (SD)	Median
Spring	564	5.3 (5.4) [a,b,c]	4.0	4.4 (5.3) [a,b,c]	3.1
Summer	418	3.0 (3.2) [d,e]	2.2	2.6 (3.3) [d]	1.8
Autumn	515	4.5 (6.0) [f]	3.0	3.5 (6.0) [f]	2.0
Winter	410	3.8 (6.7)	2.5	2.6 (7.3)	1.2

* Kruskal-Wallis test shows a significant difference in driver BC exposure (p<0.001) and adjusted BC exposure (p<0.001) between different seasons.

'a' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure (p<0.001) and adjusted BC exposure (p<0.001) between spring and summer.

'b' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure (p<0.001) and adjusted BC exposure (p<0.001) between spring and autumn.

'c' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure (p<0.001) and adjusted BC exposure (p<0.001) between spring and winter.

'd' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure (p<0.001) and adjusted BC exposure (p<0.001) between summer and winter.

'e' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure (p<0.001) between summer and autumn.

'f' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure (p<0.001) and adjusted BC exposure (p<0.001) between autumn and winter.

4.4.5 Location

The location of the drivers was split into four categories: Central London (within the current congestion charging zone); Inner London (excluding Central London); Outer London (as determined by the Office for National Statistics,[59]) and Outside London (**Figure 11**). In this analysis, there was no significant difference in drivers' exposures between central, inner and outer London locations (**Table 13**). However, there was a significant difference between all three London locations and outside London exposures ($p < 0.01$, **Appendix E**). This difference was assumed to be due to the higher concentration of vehicles in London.

Table 13: Effect of location on *'at work driving'* exposures. SD refers to standard deviation.

		BC exposure (μg/m^3) *		Adjusted BC exposure (μg/m^3) *	
	Time (hours)	Mean (SD)	Median	Mean (SD)	Median
Central London	554	5.0 (7.4) [a]	3.1	4.1 (7.4) [a]	2.3
Inner London	721	4.4 (4.7) [b]	3.1	3.4 (4.8) [b]	2.2
Outer London	362	4.3 (5.3) [c]	3.1	3.4 (5.4) [c]	2.3
Outside London	270	2.5 (2.5)	1.8	1.7 (2.5)	1.0

* Kruskal-Wallis test shows a significant difference in driver BC exposure ($p<0.001$) and adjusted BC exposure ($p<0.001$) between different locations.

'a' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure ($p<0.001$) and adjusted BC exposure ($p<0.001$) between central London and outside London.

'b' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure ($p<0.001$) and adjusted BC exposure ($p<0.001$) between inner London and outside London.

'c' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure ($p<0.001$) and adjusted BC exposure ($p<0.001$) between outer London and outside London.

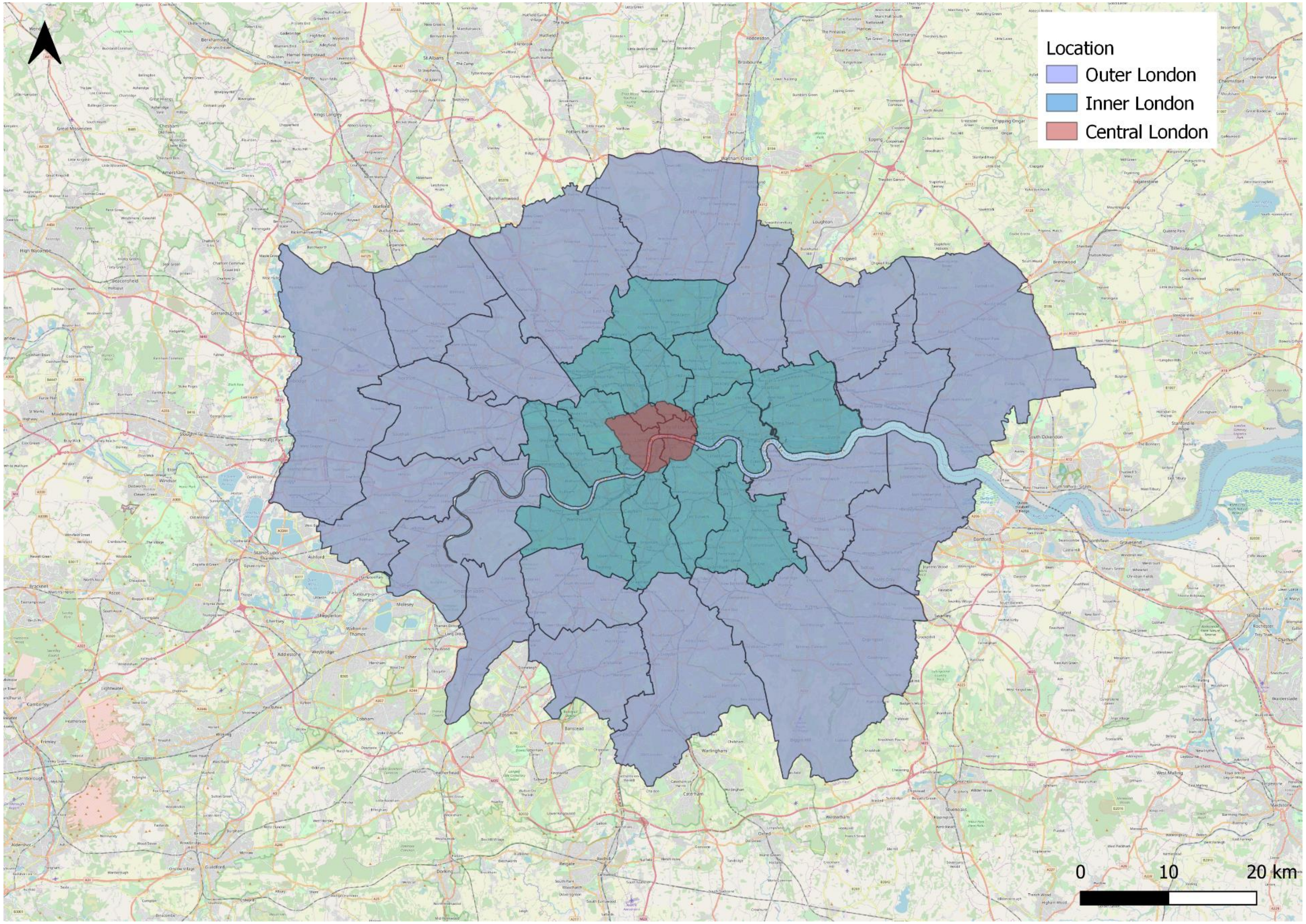

Figure 11: Map of London, showing central, inner and outer locations. Outside London is any area which is not shaded.

4.4.6 Fuel and vehicle type

Differences in fuel and vehicle type could only be observed for taxi and courier sectors since most others only used diesel vehicles or did not have enough replications of similar vehicle types to be able to make fair statistical comparisons. Comparing all diesel vehicles, irrespective of sector, against alternative fuels would introduce vehicles that could not be directly compared; therefore, data in this section is split for applicable sectors. Caution should be exercised when interpreting the data in this section as vehicle type was often dictated by the company, so differences in exposure for vehicles may be explained by company characteristics (*ie* location and time of operation) rather than by different vehicle types.

Among taxi drivers, hybrid taxis had significantly lower exposures (**Table 14**) compared to diesel fuelled alternatives ($p<0.05$). Preliminary analysis of this result found that the difference is more likely due to the airtight design of the hybrid taxi cabin[74] (reducing the infiltration of ambient pollution into the cabin) than to issues with self-pollution from the diesel taxis themselves[75].

Table 14: Effect of vehicle type for taxi drivers' *'at work driving'* exposures. SD refers to standard deviation.

		BC exposure (μg/m^3) *		Adjusted BC exposure (μg/m^3) *	
	Time (hours)	Mean (SD)	Median	Mean (SD)	Median
Mercedes Benz Vito Taxi - Diesel	26	5.4 (4.3) ^{a,b}	4.7	4.4 (4.2) ^{a,b}	3.6
TX4 Taxi – Diesel	249	8.0 (6.8) ^{c}	6.3	7.2 (6.8) ^{c}	5.4
TXe Taxi – Hybrid	189	3.7 (3.4)	2.9	2.8 (3.3)	2.0

* Kruskal-Wallis test shows a significant difference in driver BC exposure ($p<0.001$) and adjusted BC exposure ($p<0.001$) between different taxi vehicle types.

'a' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure ($p<0.001$) and adjusted BC exposure ($p<0.001$) between Mercedes Benz Vito Taxi and TX4 Taxi.

'b' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure ($p<0.001$) and adjusted BC exposure ($p<0.001$) between Mercedes Benz Vito Taxi and TXe Taxi.

'c' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure ($p<0.001$) and adjusted BC exposure ($p<0.001$) between TX4 Taxi and TXe Taxi.

For couriers, Ford Transit vans had the highest exposures compared to other models. However, the electric vans monitored did not exhibit lower exposure compared to other diesel van types (**Table 15**). This analysis highlighted differences in exposures experienced between different vehicle types. Nevertheless, more specific research methodologies are required to be able to precisely determine the cause of the differences observed.

Table 15: Effect of vehicle type for courier drivers' *'at work driving'* exposures. SD refers to standard deviation.

		BC exposure (µg/m^3) *		Adjusted BC exposure (µg/m^3) *	
	Time (hours)	Mean (SD)	Median	Mean (SD)	Median
Ford Transit Van – Diesel	74	8.7 (12.9) [a]	3.2	7.5 (12.9) [a]	2.2
Nissan Voltia – Electric	56	4.2 (4.2) [b]	3.0	3.2 (4.0) [b]	1.9
Vauxhall Vivaro Van – Diesel	43	2.9 (2.7)	2.1	2.0 (3.6)	1.2
Unspecified Van – Diesel	16	3.3 (2.1)	3.0	1.8 (3.5)	1.2

* Kruskal-Wallis test shows a significant difference in driver BC exposure ($p<0.001$) and adjusted BC exposure ($p<0.01$) between different courier vehicle types.

'a' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure ($p<0.001$) and adjusted BC exposure ($p<0.01$) between Ford Transit Van and Nissan Voltia.

'b' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure ($p<0.01$) and adjusted BC exposure ($p<0.05$) between Nissan Voltia and Vauxhall Vivaro Van.

4.4.7 Mixed effects model for drivers' exposures

A mixed effects model was used to adjust for the interactions between variables and thus better describe the individual effect of each determinant on drivers' exposure. Initially, all possible explanatory variables were included in the model to identify those factors which produced the model with the lowest corrected Akaike information criterion. The dependent variable was BC exposure for *'at work driving'* at a 15-minute resolution, with the explanatory variables included in **Table 16**. There were a number of variables recorded but were not included in the full model for various reasons, including: 'vehicle type' due to possible collinearity issues with the sector variable; 'precipitation' because of the substantial number of missing records which would reduce the number of observations available for testing; and 'ventilation settings' as this variable should only be analysed when windows were closed. The model used untransformed driving exposure values due to the ease of interpretation of the output estimates. However, the optimal model was also completed for logged values and the statistically significant variables did not substantially change (**Appendix F**). Therefore, the unadjusted model is presented in the results.

Table 16: List of variables included in full mixed effects model.

Variable name	Variable type	Variable nature
Driving speed	continuous	Urban
Background BC	continuous	Meteorological
Air temperature	continuous	Meteorological
Relative humidity	continuous	Meteorological
Wind speed	continuous	Meteorological
Day of week	categorical	Temporal
Time of day	categorical	Temporal
Season	categorical	Temporal
School holidays	categorical	Temporal
Location	categorical	Geographical
Sector	categorical	Occupational
Fuel type	categorical	Vehicle
Smoker	categorical	Participant
Predominant window position for shift	categorical	Participant

The optimal model for analysis was determined to be:

$$\begin{aligned}(BC\ driving)_{ij} = \ &\alpha\ + (participant)_i + \beta_1(background\ BC)_{ij} + \beta_2(fuel)_{ij} + \beta_3(location)_{ij} \\ &+ \beta_4(time\ of\ day)_{ij} + \beta_5(sector)_{ij} + \beta_6(smoker)_{ij} + \beta_7(driving\ speed)_{ij} \\ &+ \beta_8(day\ of\ week)_{ij} + \beta_9(window)_{ij} + \beta_{10}(wind\ speed)_{ij} + \varepsilon_{ij}\end{aligned}$$

Where i is the index of each participant and j is the index of the 15-minute average in-cabin BC exposure, background concentration, driving speed or meteorological parameter; α represents the fixed mean exposure for all participants; $(participant)_i$ is the random effect of each participant; the βs are the fixed effects of each variable; and ε_{ij} is the residual. Out of all variables in the full model, only season, air temperature and relative humidity were not included in the optimal model. The descriptive analysis showed a significant seasonal effect on exposures (**section 4.4.5**). However, once this was adjusted for other factors, this variable was not found to be influential on drivers' exposure and was therefore excluded from the final model.

The optimal model (**Table 17**) demonstrated that background BC was a significant predictor of driving exposure as every 1 μg/m^3 increase in background concentration resulted in a 0.48 μg/m^3 increase in driver exposure. While this effect appeared relatively high, the third quartile background BC level was only 1.1 μg/m^3. Fuel type was not a variable that significantly explained drivers' exposure; however, the hybrid taxis were marginally non-significant (p= 0.06) and, compared to diesel vehicles, explained a 4.22 μg/m^3 reduction in driver exposure. The location results were all statistically significant ($p < 0.01$). Drivers' exposures increased with proximity to the city centre and central London exposures were 0.77 μg/m^3 higher compared to outer London.

Time of day exposures found significantly higher exposures of 0.60 μg/m^3 during evening peak times compared to daytime exposures. There were no other significant differences observed for other times of the day. The sector exposures were only significantly higher for taxi drivers, with this sector being 5.02 μg/m^3 higher compared to bus drivers' exposures.

Despite the significantly higher exposures observed for smoker status in the descriptive statistics, the mixed effects model showed no significant difference between exposures apart from between those participants who didn't report their smoking status and non-smokers.

Surprisingly, driving speed had a positive relationship with exposure, as the majority of previous studies have suggested that lower speeds result in higher exposures[36]. However, other studies have found that periods of acceleration and speeds of greater than 75 km/hr led to higher vehicle emissions[76], which could possibly explain the positive relationship observed between speed and exposure. The effect of vehicle speed in this study was comparatively low with an increase of 0.06 μg/m^3 per 1 km/hr increase in speed 1 km/hr and the third quartile speed for drivers only being 6 km/hr.

There was a significantly lower exposure of 1.35 μg/m^3 for drivers working at the weekend compared with weekdays, which is most likely due to the reduced number of vehicles on the road in the former . There is also substantially lower heavy goods vehicle traffic at the weekend[73], which is also thought to be an important contributor to BC levels.

Window position results followed the descriptive statistics as there was a 0.44 μg/m^3 increase in exposure for drivers who had their windows open, rather than closed, for their shift. 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 0.27 μg/m^3. Nevertheless, the magnitude of wind speed experienced during this study was relatively low with the 3rd quartile of wind speed being 5 m/s.

Table 17: Parameters estimate from optimal mixed-effects model to explain determinants of *'at work driving'* BC exposures

Fixed Effect determinants	Categorical Comparison	Estimate	95% CI (lower, upper)	p-Value
(Intercept)		2.78	-0.52, 6.09	ns (0.1)
Background BC (µg/m^3)		0.48	0.33, 0.63	< 0.0001
Fuel	Electric ~ Diesel	-1.38	-5.47, 2.71	ns
	Hybrid ~ Diesel	-4.22	-8.65, 0.20	ns (0.06)
Location	Outside ~ Outer London	-1.26	-1.71, -0.81	< 0.0001
	Inner London ~ Outer London	0.45	0.14, 0.77	0.005
	Central London ~ Outer London	0.77	0.39, 1.15	< 0.0001
Time of day	Night time ~ Day time	0.06	-0.26, 0.38	ns
	Morning peak ~ Day time	-0.12	-0.38, 0.14	ns
	Evening peak ~ Day time	0.60	0.27, 0.93	< 0.0001
Sector	Courier ~ Bus	2.61	-1.62, 6.84	ns
	Emergency Services ~ Bus	-0.55	-4.17, 3.07	ns
	Heavy Freight ~ Bus	0.01	-3.88, 3.90	ns
	Taxi ~ Bus	5.02	0.96, 9.09	0.02
	Utility Services ~ Bus	-0.58	-5.00, 3.84	ns
	Waste Removal ~ Bus	0.41	-3.51, 4.33	ns
Smoker Status	Not reported ~ Non-smoker	4.66	1.26, 8.06	0.008
	Smoker ~ Non-smoker	2.14	-0.40, 4.69	ns (0.1)
Driving speed (km/hr)		0.06	0.03, 0.09	< 0.0001
Day of week	Weekend ~ Weekday	-1.35	-1.77, -0.92	< 0.0001
Predominant window position	Not reported ~ Window closed	0.69	-2.48, 3.86	ns
	Windows open ~ Windows closed	0.44	0.04, 0.85	0.03
Wind speed (m/s)		-0.27	-0.34, -0.19	< 0.0001

ns – not significant

From the mixed effects model, it appeared that the largest determinant on exposure was the sector the drivers worked in. Taxi drivers had significantly higher exposures compared to bus drivers. However, contrary to results presented in **section 4.2**, no other sectors showed significant difference in BC exposures compared to bus drivers. In terms of factors which drivers or employers could potentially control, window position, day of operation, location (ie route choice) and time of day all significantly contributed to exposure. Other significant determinants of exposure that were outside of drivers, or employers' direct control were meteorological factors, vehicle speed and background concentrations. However, these had a comparatively small absolute effect on exposure levels.

4.4.8 Determinants of drivers' exposure

This section identified some of the main determinants of driver exposure, analysing determinants individually first and then using a mixed-effects model. Predominant window position, driver location, time of day, wind speed, vehicle speed, background BC concentrations and day of week all had a significant effect on driver exposure. While some of these changes may not be commercially or practically viable for drivers to change (ie conducting work at the weekend instead of on weekdays or avoiding peak evening driving periods), closing windows while driving is one simple behaviour change which can significantly reduce drivers' exposure. Recirculate ventilation settings also appeared to reduce exposure, although drivers should be cautious when using this setting for long periods due to the risk of increased CO_2 levels within the cabin, which may affect cognitive performance[77-79].

It also appeared that vehicle type can affect driver exposure, as observed in the difference in exposures between driving hybrid and diesel taxis. While further work is needed to specifically evaluate the cause of this difference, it is likely that better designed airtight cabins could significantly reduce drivers' exposure. Furthermore, if newer vehicles also have zero tail pipe emissions, this will also reduce the ambient levels of BC concentrations (another significant determinant of driver exposure) and ultimately reduce drivers' exposure.

4.5 Intervention study results

4.5.1 Overview of intervention study exposures

The aim of the intervention study was to investigate the effectiveness of practical low-cost interventions that employers could easily implement to reduce drivers' exposures. The efficacy of in-cabin filters was analysed in this study. The intervention results found average '*at work'* exposures of 2.3 ± 2.0 μg/m^3 and '*at work driving'* exposures of 2.7 ± 2.3 μg/m^3 (**Table 18**). These were significantly lower compared to the baseline study exposures at 3.1 ± 3.5 μg/m^3 and 4.2 ± 4.7 μg/m^3 respectively ($p<0.05$). Similar to the baseline results, there was a significant difference in average exposures 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 ($p=0.14$) and '*at work not driving*' and '*commuting*' exposures ($p=0.09$).

The lower exposures recorded could relate to several factors: the mix of sectors monitored; the introduction of the Ultra-Low Emission Zone in London, in April 2019; the study only being conducted in spring and summer; and possibly the use of in-cabin filters. However, the medians were similar between the two studies, suggesting there was a greater proportion of high exposures experienced in the baseline study.

Four out of the six companies participating in the intervention study were also measured in the baseline study. However, there was a new sector analysed, 'passenger transport', where drivers transported hospital patients between hospitals and their homes. Despite being in central London and driving for the majority of their shifts, these drivers were found to be exposed to some of the lowest exposures measured. There is some uncertainty as to why these drivers had very low exposures but this could possibly be explained by the vehicle type and the route of travel for these drivers, although this requires further analysis. However, as in the baseline study, taxi, waste removal and couriers were the most highly exposed sectors (**Table 19**).

Table 18: Summary statistics by participant in the intervention study for average, minimum, median and maximum BC exposures at one-minute resolution across different activities.

Activity	Number of participants	Mean (standard deviation) for hours monitored	BC exposure (µg/m^3) Mean (SD) participant*	Minimum participant	Median participant	Maximum participant
At work driving	42	15.5 (9.0)	2.7 (2.3)	0.8	2.2	15.5
At work not driving	42	11.4 (7.3)	1.8 (1.7)	0.2	1.3	7.3
At work	**42**	**26.9 (9.1)**	**2.3 (2.0)**	**0.3**	**2.0**	**11.9**
Commuting	42	3.0 (2.8)	3.1 (4.0)	0.0	1.9	15.7
At home	42	44.3 (29.1)	0.7 (0.4)	0.1	0.6	2.0
Not at work	**42**	**47.3 (29.1)**	**0.9 (0.8)**	**0.1**	**0.8**	**3.7**
All times	**42**	**74.2 (31.4)**	**1.4 (0.8)**	**0.2**	**1.3**	**4.4**

*SD= is presented as the arithmetic standard deviation between participants

Table 19: Summary statistics of at work BC exposures and time spent for different sectors by shift in the intervention study. Sectors are ordered from highest at work exposure to lowest.

			Mean (standard deviation) BC exposure (µg/m^3)			Mean (standard deviation) time spent in hours		
Sector	**Participants**	**Shifts**	**At work driving**	**At work not driving**	**At work total**	**At work driving**	**At work not driving**	**At work total**
Taxi	5	19	5.0 (6.4)	2.5 (2.5)	4.1 (5.1)	5.9 (1.9)	1.7 (1.4)	7.5 (2.5)
Waste Removal	14	47	3.2 (2.1)	2.9 (3.2)	3.1 (2.3)	5.6 (0.9)	1.8 (0.7)	7.4 (1.3)
Courier	5	20	2.8 (1.0)	1.2 (0.6)	2.1 (0.8)	4.7 (1.0)	3.7 (1.0)	8.4 (1.0)
Passenger Transport	9	30	1.8 (0.7)	1.0 (0.3)	1.5 (0.5)	5.1 (1.9)	3.4 (1.3)	8.6 (2.5)
Utility Services	9	29	1.7 (1.3)	0.9 (1.0)	1.0 (0.9)	1.1 (0.4)	6.4 (1.6)	7.3 (1.5)
Total	**42**	**145**	**2.8 (2.9)**	**1.8 (2.3)**	**2.3 (2.5)**	**4.7 (2.1)**	**3.3 (2.1)**	**7.8 (1.9)**

4.5.2 Descriptive statistics on the effect of in-cabin filters on drivers' exposure

The primary aim of the intervention study was to observe whether in-cabin filters reduced *'at work driving'* exposure to workers over their entire shift. Therefore, descriptive statistics in this instance are presented on a per shift basis. Again, as with the baseline analysis, the efficacy of the filters is analysed separately, before all variables were placed into a mixed effects model. Of the 145 shifts monitored, only 140 had measurements where workers were driving.

Table 20 showed a slight decrease between drivers who drove with an in-cabin filter (2.8 ± 3.4 μg/m^3) compared to those who did not (3.0 ± 2.4 μg/m^3), although this difference was not statistically significant (p= 0.08). Exposures adjusted for background concentrations showed similar results. There were four shifts by two participants that were substantially higher compared to the rest, with these exposures being above 10 μg/m^3 as indicated on **Figure 12**. To remove the effect of these very high shifts on in-cabin filter use, not only were the high shifts removed but all eight shifts from the two participants were removed to avoid any bias in the results. By removing these shifts there was a significant difference (p <0.05) between those drivers using in-cabin filters (2.2 ± 1.1 μg/m^3) and those not using them (2.7 ± 1.5 μg/m^3) (**Table 21**). However, extreme caution should be taken when interpreting these results since the exposures that were removed from the analysis were real exposures and these high concentrations do suggest there are certain circumstances in which the in-cabin filter appears not to work efficiently.

Table 20: Effect of in-cabin filters on *'at work driving'* exposure. SD represents standard deviation.

		BC exposure (μg/m^3) *		Adjusted BC exposure (μg/m^3) *	
	Shifts	Mean (SD)	Median	Mean (SD)	Median
In-cabin filter used	66	2.8 (3.4)	2.1	2.0 (3.4)	1.3
In-cabin filter not used	65	3.0 (2.4)	2.5	2.3 (2.5)	1.8
Not reported	9	1.5 (0.6) [a,b]	1.4	1.0 (0.6) [a]	0.8

* Kruskal-Wallis test shows a significant difference in driver BC exposure (p<0.01) and adjusted BC exposure (p<0.05) for use of in-cabin filters.

'a' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure (p<0.01) and adjusted BC exposure (p<0.05) between not reported and in-cabin filter not used.

'b' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure (p<0.05) between not reported and in-cabin filter used.

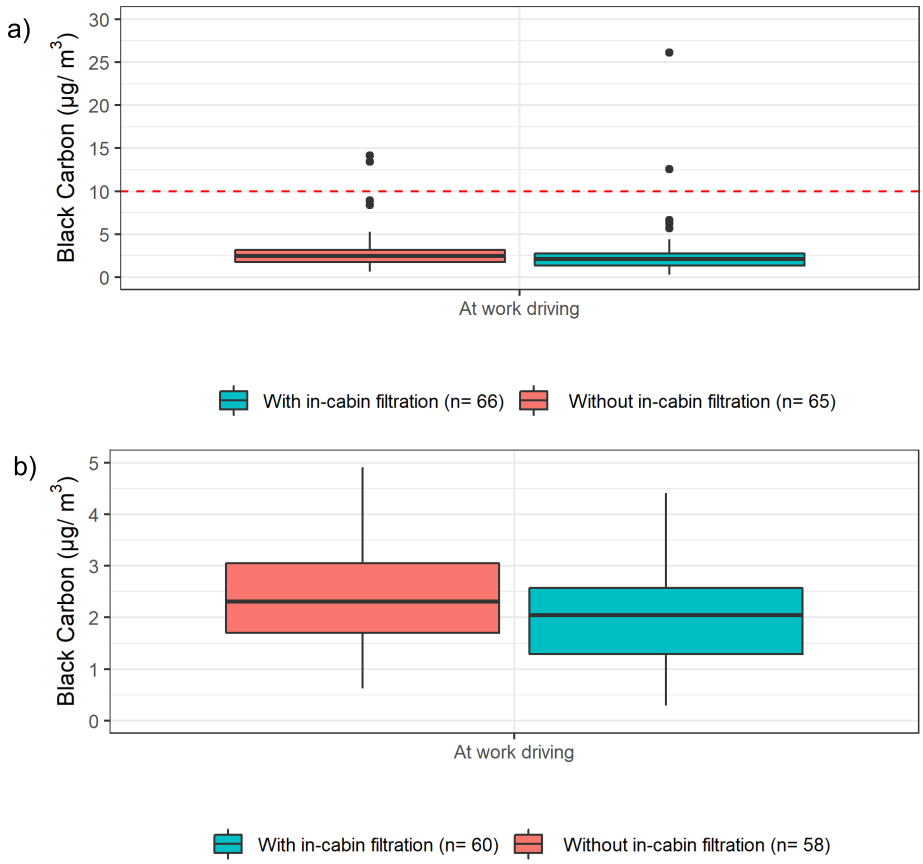

Figure 12: a) Box plot of BC exposures by shift with and without the use of in-cabin filters. The red dotted line shows the four shift exposures above 10 µg/m^3. b) Box plot of BC exposures by shift excluding outliers with and without the use of in-cabin filters.

Table 21: Effect of in-cabin filters on *'at work driving'* exposure excluding two participants with high exposures. SD represents standard deviation.

		BC exposure (µg/m^3) *		Adjusted BC exposure (µg/m^3) *	
	Shifts	Mean (SD)	Median	Mean (SD)	Median
In-cabin filter used	62	2.2 (1.1) [a]	2.1	1.4 (1.1) [a]	1.2
In-cabin filter not used	61	2.7 (1.5)	2.3	2.0 (1.5)	1.8
Not reported	9	1.5 (0.6) [b]	1.4	1.0 (0.6) [b]	0.8

* Kruskal-Wallis test shows a significant difference in driver BC exposure (p<0.01) and adjusted BC exposure (p<0.01) for use of in-cabin filters.

'a' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure (p<0.05) and adjusted BC exposure (p<0.05) between in-cabin filter used and in-cabin filter not used.

'b' Pairwise *post hoc* Dunns test shows a significant difference in driver BC exposure (p<0.01) and adjusted BC exposure (p<0.05) between not reported and in-cabin filter not used.

Instructions on the use of the in-cabin filters state that, for optimal results, they should be used when windows are closed. Drivers were asked to keep their windows closed while driving during the intervention study; however, due to the warm weather and some vehicles not having air-conditioning available, this was not always practical. Consequently, only 32 per cent of the shifts monitored during the study saw drivers driving with their windows closed. Therefore, the shifts were further split so that only data where windows were closed was analysed. The results from this were inconclusive (**Table 22**): while using the in-cabin filters resulted in lower average exposures, the difference was not significant (p=0.10).

Table 22: Effect of in-cabin filters on 'at work driving' exposure for shifts when windows were closed. SD represents standard deviation.

		BC exposure (μg/m^3)		Adjusted BC exposure (μg/m^3)	
	Shifts	Mean (SD)	Median	Mean (SD)	Median
In-cabin filter used	20	3.3 (5.5)	1.9	2.6 (5.5)	1.1
In-cabin filter not used	18	3.8 (3.8)	2.9	3.2 (3.9)	1.9

4.5.3 Mixed effects model for in-cabin filter use

A mixed effects model was used to isolate the effect of in-cabin filters on *'at work driving'* exposure. Like the baseline model, the participant was used as a random effect in the model. Shift exposure data was included in the mixed effects model as the dependent variable. However, the 15-minute resolution was also analysed to account for time-dependent determinants (ie location, time of day etc.) that shift level exposures could not capture, yet this did not change the statistically significant effect of the use of in-cabin filtration devices (**Appendix G**).

Table 23 presents the variables that were included in the intervention model. Some variables were not included in the full model as there were not enough replications. For example, there was only one shift monitored at the weekend, so the day of the week variable was not included.

Table 23: List of variables included in the full intervention mixed-effects model.

Variable name	**Variable type**	**Variable nature**
Average shift vehicle speed	continuous	Urban
Average background BC for shift	continuous	Meteorological
Average air temperature for shift	continuous	Meteorological
Average wind speed for shift	continuous	Meteorological
Day or night shift	categorical	Temporal
% of shift spent in morning peak	continuous	Temporal
% of shift spent in evening peak	continuous	Temporal
% of shift spent in central London	continuous	Geographical
% of shift spent in outer London	continuous	Geographical
% of shift spent outside London	continuous	Geographical
Sector	categorical	Occupational
Fuel type	categorical	Vehicle
Smoker	categorical	Participant
Use of in-cabin filter	categorical	Participant
Predominant window position for shift	categorical	Participant

All possible explanatory variables were placed in the full model and assessed for every different combination to produce an optimal model with the lowest corrected Akaike information criterion. Unlike the baseline model, only a few variables remained in the optimal model.

The optimal intervention model is presented as:

$$(bc\ driving)_{ij} = \alpha + (participant)_i + \beta_1(background\ bc)_{ij} + \beta_2(fuel)_{ij} + \beta_3(filter\ use)_{ij} + \beta_4(sector)_{ij} + \beta_5(smoker)_{ij} + \varepsilon_{ij}$$

Where i is the index of each participant and j is the index of the shift average BC exposure for *'at work driving'*, background concentrations, driving speed or meteorological measurement, α represents the fixed mean exposure for all participants, $(participant)_i$ is the random effect of each participant, the βs are the fixed effects of each variable and ε_{ij} is the residual.

Table 24 presents the optimal model with all variables included. There were only two statistically significant results. An increase of 1 µg/m^3 in average background BC concentrations resulted in a 2.21 µg/m^3 increase in shift exposure, while taxi drivers had a 3.51 µg/m^3 higher average shift exposure compared to courier drivers. Like the descriptive results, in-cabin filter use did not have a significant effect on drivers' exposures.

Table 24: Parameters estimate from optimal intervention mixed-effects model to explain the effectiveness of in-cabin filters on shift *'at work driving'* BC exposures.

Fixed Effect determinants	Categorical Comparison	Estimate	95% CI (lower, upper)	p-Value
(Intercept)		0.57	-1.70, 2.83	ns
Background BC (µg/m^3)		2.21	1.19, 3.24	<0.0001
Fuel type	Hybrid ~ Diesel	-3.25	-8.08, 1.57	ns
In- cabin filter use	Not reported ~ In-cabin filter not used	-0.38	-5.25, 4.49	ns
	In-cabin filter used ~ In-cabin filter not used	-0.05	-0.73, 0.62	ns
Sector	Passenger transport ~ Courier	-0.73	-3.30, 1.83	ns
	Utility services ~ Courier	-0.08	-2.94, 2.79	ns
	Taxi ~ Courier	3.51	0.49, 6.53	0.03
	Waste Removal ~ Courier	0.48	-1.79, 2.74	ns
Smoker Status	Not reported ~ Non-smoker	0.37	-5.08, 5.82	ns
	Smoker ~ Non-smoker	1.22	-0.87, 3.31	ns

ns – not significant

However, as with the descriptive analysis, the mixed-effects model was re-run after excluding the two participants who experienced particularly high exposures. This resulted in a significant decrease in driver exposures with in-cabin filter use (**Table 25**). In this amended model, the use of the in-cabin filter resulted in a statistically significant 0.42 µg/m^3 decrease in BC exposure when compared with drivers who did not use the device. The change also reduced the effect of background BC, with a 1 µg/m^3 increase resulting in a 1.39 µg/m^3 increase in shift exposure. There was also a significant effect for being a smoker with a 1.11 µg/m^3 increase in shift exposure for being a smoker when compared with a non-smoker.

Table 25: Parameters estimate from optimal intervention mixed-effects model to explain the effectiveness of in-cabin filters on shift *'at work driving'* BC exposures. The two high exposure participants were removed.

Fixed Effect determinants	Categorical Comparison	Estimate	95% CI (lower, upper)	p-Value
(Intercept)		1.43	0.50, 2.35	0.005
Background BC (μg/m^3)		1.39	0.86, 1.92	<0.0001
Fuel type	Hybrid ~ Diesel	-0.12	-2.04, 1.79	ns
In-cabin filter use	Not reported ~ In-cabin filter not used	-0.90	-2.83, 1.03	ns
	In-cabin filter used ~ In-cabin filter not used	-0.42	-0.77, -0.07	0.02
Sector	Passenger transport ~ Courier	-0.65	-1.64, 0.35	ns
	Utility services ~ Courier	-0.18	-1.31, 0.95	ns
	Taxi ~ Courier	0.13	-1.13, 1.39	ns
	Waste Removal ~ Courier	0.41	-0.47, 1.30	ns
Smoker Status	Not reported ~ Non-smoker	0.62	-1.51, 2.75	ns
	Smoker ~ Non-smoker	1.11	0.26, 1.96	0.02

ns – not significant

4.5.4 Effect of in-cabin filters on drivers' exposure

The results on the effectiveness of in-cabin filters to reduce drivers' exposure to BC were inconclusive. There appeared to be situations where, despite using the in-cabin filters, the drivers' exposures were very high, as was the case with two participants. However, the precise reasons behind these high exposures would require more detailed knowledge of the sources of exposure (ie the type of vehicles they followed and the level of congestion), which were not available. When these high exposure participants were removed, results revealed a significant reduction for *'at work driving'* exposure; however, the absolute reduction in exposure was relatively low and the mixed effects model indicated a decrease of 0.4 μg/m^3 over a shift.

An important point to note is that drivers were provided with these devices for specific shifts. While it is likely that the majority of participants used them in the way intended, we could not determine whether or not they were turned on during the shift. Companies should also consider the practicality of these devices for their workforce as some drivers reported annoyance with noise or air blowing, which could also reduce drivers' compliance in using them. From the current results, there is inconclusive evidence on the effectiveness of in-cabin filters and, consequently, further detailed analysis is still required to robustly assess their efficacy.

5. Discussion

5.1 Characterising professional drivers' exposure

This study is one of the first to provide insight into the exposure characteristics of urban professional drivers and it is the largest real-world in-vehicle personal exposure study to date. Exposures for professional drivers were 2.6 times higher for all times *'at work'* compared to those outside of work. *'At work driving'* was associated with the highest BC exposures compared to other activities, contributing 36 per cent of drivers' total daily BC exposure, despite accounting for only 19 per cent of their time. Comparing these contributions to studies on populations with a fixed place of work or school, Dons *et al* [41] found that full-time workers spent 17 per cent of time at work but this only contributed to 12 per cent of their total BC exposure. Rivas *et al*[59] found school children spent 31 per cent of time at school, which contributed 33 per cent of their total exposure. The high contribution of daily BC exposure from *'at work driving'* in this study highlights the fact that professional drivers are disproportionately affected by BC and, by association, diesel exhaust fumes whilst working. The results also suggest that some professional driving sectors, such as taxi drivers, couriers and waste removal drivers, are more at risk of high exposure than others. Roles where driving is infrequent, such as in emergency services, had lower average *'at work'* exposure.

The study found similar trends to previous personal exposure studies, with the lowest average exposures experienced in the home and higher exposures experienced while commuting[10,22,59]. However, an important difference with this study, when compared to others, is the high '*at work'* exposures measured for professional drivers. Periods of high exposure during work were typically observed while driving. Evidence suggests that these were caused by random individual events where the vehicle cabin is infiltrated by pollutants from a direct local source, such as when following a high polluting vehicle, or when transiting through a congested street canyon. This has been observed in other exposure studies[19,22,24]. Exposures outside of work times were typically low and the highest among these were largely experienced while *'commuting'*. However, there were also some sporadic high exposures which occurred *'at home'* for some participants (**Figure 5**). These are likely to have been caused by heating or cooking activities undertaken inside the house[10,80].

A closer examination of the individual driver exposures indicated that exposure spikes were highly influential on driver exposure, with BC levels at times greater than 100 $\mu g/m^3$ trapped within the vehicle cabin for periods of up to an hour. Notably, exposures to diesel exhaust at this level have previously been associated with adverse airway responses in healthy volunteers in experimental studies[9] , and adverse cardiovascular responses at only 2-3 times this level[81]. Qualitative analysis of these spikes found that they often occurred sporadically, but a number of spikes were observed when drivers either travelled through tunnels or drove in congestion (often within central London), and drove in areas where vehicles congregate, such as in car parks or depots. Reducing the occurrence and duration of exposure spikes is likely to substantially reduce driver exposure and warrants further investigation.

In several countries, exposure to hazardous substances, including diesel exhaust, is covered by law. In the United Kingdom, employers are legally required to assess whether employees are at risk from diesel exhaust exposure[7]. However, there is currently no occupational exposure limit for BC, although the EU has recently agreed to implement a 50 µg/m^3 exposure limit from diesel engine exhaust emissions (EC) averaged over an eight-hour shift. This is due to be enforced in 2023[48]. No participants were over this occupational limit, with the highest BC shift exposure measured at 39.8 µg/m^3. There are no standard conversion factors for BC to EC as this varies depending on location, time of day and source of emissions. However, the two are highly correlated and, in London in 2016, BC ranged from 1.08 times higher than EC at the urban background North Kensington site and 1.25 times higher at the kerbside Marylebone Road site[50].

There is no applicable ambient (ie 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 World Health Organisation (WHO) ambient air quality guideline for $PM_{2.5}$ [82]. This is set at 25 µg/m^3 averaged over 24 hours. There was only one instance when a participant was over the 24-hour WHO $PM_{2.5}$ guideline (BC at 30.9 µg/m^3) but short-term exposures were intermittently higher than this value. Again, there is no standard conversion for BC to $PM_{2.5}$ but 2016 measurements in London had BC comprising 9 per cent of $PM_{2.5}$ mass at North Kensington and 31 per cent of $PM_{2.5}$ mass at Marylebone Road[50]. While exposures were generally lower than these limits, it should be noted that there have been studies which have found significant health effects for BC at values lower than 1.5 µg/m^3[44,83,84].

5.2 Determinants of drivers' exposure

Determinants of exposure were first assessed individually and then through a mixed-effects model. The dominant variables that increased driver exposure included:

- Driving with windows open
- Driving within London, with central London resulting in the highest exposures
- Working as a taxi driver
- Driving in the evening peak between 4 pm – 7 pm
- Working on weekdays compared to the weekend
- Higher background BC concentrations
- Faster driving speeds
- Lower wind speeds.

The variables above are determinants which have been robustly tested both individually and in the mixed-effects model. Other determinants that require further validation, which may also result in higher driver exposures, include vehicle type (specifically those that have high air exchange rates); route choice (particularly when driving on heavily congested routes and through tunnels); being a smoker; and using ventilation settings not set to recirculate.

One of the contentious findings in this study is the notion that faster driving speeds lead to higher levels of driver exposure, with studies actually suggesting the opposite effect [36]. However, the mixed-effects model assumed a linear relationship, which may be incorrect as higher driver exposures have been observed at both low and high vehicle speeds[19].

These determinants have been identified in varying degrees in a number of previous studies [16,19-25]; however, there has been no robust quantification of which determinants are the most influential and no studies have been conducted with professional drivers across a wide range of vehicle types and in a variety of occupational sectors.

5.3 Interventions to reduce drivers' exposure and implications for fleet operators

This analysis provides insight into the types of interventions that could be implemented in order to reduce drivers' exposure. From the determinants analysis, there were a few determinants that are outside both the drivers and employer's control, such as meteorological factors, vehicle speed and background BC levels.

There are several steps which could be taken to reduce exposures. The simplest and most effective way to reduce exposures would be for drivers to keep a vehicle's windows closed. Other possible changes could include reducing driving time on weekdays, in the evening peak hours and in congested urban areas. Altering route choice may also be an effective way to reduce drivers' exposures, particularly if drivers can avoid heavily congested areas and tunnels. While there are likely to be logistical constraints to fleet operators in implementing some of these changes, this research provides a business case for those fleets wanting to operate at different times.

This study also found reduced exposures when vehicle ventilation was set to recirculate mode. Other studies have found recirculation settings can reduce exposures by up to 75 per cent[20,52]. While this appears to be an effective way of reducing exposures, we would suggest caution in using this setting due to the accumulation of CO_2[77,78]. Drivers should only employ this setting for short time periods in order to avoid excess CO_2 build-up, which could affect drivers' cognitive function[78].

From the present analysis, there is inconclusive evidence on the effectiveness of in-cabin filters in reducing drivers' exposures. Another study has suggested reduced health effects for taxi drivers when using high-efficiency cabin air (HECA) filters built into the vehicle's ventilation system[39]. However, further testing is still needed before this intervention can be recommended as an effective way to reduce exposures under real-world driving conditions.

Other more expensive interventions could include upgrading fleets to newer, more airtight vehicle cabins, which would also reduce exposure for drivers[23]. If these new vehicles have zero tailpipe emissions, this would also reduce ambient diesel exhaust concentrations and would ultimately reduce exposures to drivers.

Fleet operators should also consult their employees to assist in implementing these changes effectively. For example, conversations with some participants suggested that having air conditioning available in vehicles is likely to improve compliance among drivers keeping windows closed during their shift. Other considerations, like assessing the likelihood that drivers will use in-cabin filters, should also be evaluated. Furthermore, automated systems, where available, may be more effective in implementing these changes successfully.

Another impact of this personal exposure study is its ability to raise awareness and engage with stakeholders in relation to air pollution exposure[85,86]. Increased awareness is also likely to encourage best practice among this occupational group. Toolbox talks or similar should also be encouraged by fleet operators when implementing these changes.

Policy decisions aimed at decreasing congestion levels and regulating emissions from vehicles, including investment in cleaner fuels, will also reduce drivers' exposure. While some of these policies, such as congestion charging zones and emission standards, have been implemented in cities across Europe[87,88], wider and more stringent application will benefit professional drivers.

We acknowledge that, in parallel with altered driver behaviour, there will need to be continued investment in the development and validation of technological solutions to reduce incabin pollutant concentrations. In this report, we have highlighted one potential solution, using in-cabin filters but other solutions will need to be developed to keep in-cabin CO_2 concentrations within safe limits. For professional drivers, there must be a much stronger focus on vehicle certification for in-cabin air quality, coupled with greater effort to minimise pollution emissions for other road users.

5.4 Limitations and future work

While this study had several important findings, there were some limitations. Several variables, such as window position, ventilation settings and the use of in-cabin filtration devices, relied on participants' self-reporting and compliance, which could not be guaranteed. An electronic record on the device or within the vehicle, and simultaneous CO_2 measurements, would have provided a better insight into these variables and should be considered in future studies.

We had difficulty recruiting some important professional driving sectors and might, therefore, have missed some pertinent sector-specific interventions. Reasons given by sectors for not participating included organisational policy in not taking part in research studies, or companies deeming it to be a commercial risk to take part in this study.

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. Taxi drivers appeared to be the most 'at risk' sector from diesel emissions, for example. Consequently, a more focused study on this sector may provide more specific interventions for this group. Although we used mixed-effects models to best adjust for confounding variables, using controlled testing to complement current results might be another way to fully assess interventions.

This study was one of the first to provide a detailed characterisation of professional drivers' exposures in real world urban conditions and raised some further research topics. Future work could include:

- a specific analysis of the influence of vehicle type on drivers' exposure, to better identify and explain which vehicles best reduce driver exposure, including simultaneous inside and outside measurements to determine vehicles' air exchange rates
- further testing on in-cabin filters and their effectiveness for more robust results on their efficacy
- a measure of congestion and detailed analysis of vehicle movements for routing and identifying location-specific ways to reduce exposure for drivers
- an analysis of driver behaviour, particularly to identify the effect of driver habits on exposure
- finally, a significant finding of this study is the existence of air pollution spikes and their duration. Further work should be conducted on the viability of detecting when a spike occurs using a real time in-vehicle pollution sensor. If the sensor is integrated within the vehicle's ventilation system, this could assist with automatically reducing the duration of an air pollution spike.

6. Conclusion and recommendations

We have conducted the largest real-world in-vehicle personal exposure study to date. The study found that professional drivers are disproportionately affected by diesel exhaust exposure, as the *'at work driving'* activity contributed the most to participants' daily exposure.

The risk of diesel exhaust exposure to workers has been highlighted in IOSH's 'No Time To Lose' campaign[7]. In the United Kingdom, employers have a legal duty to consider the risk of cancer to their employees from work activities and to act to reduce this risk if there are activities of concern. Therefore, companies with professional drivers need to implement changes to reduce or stop exposure to diesel exhaust. Both employers and drivers are encouraged to change behaviours that could facilitate a reduction.

The following set of recommendations are made as a result of this study:

- the simplest change drivers can make to reduce their exposure is to drive with their windows closed. Employers should also consider having air conditioning available in all vehicles to assist with driver compliance, particularly when driving during warmer months
- drivers should use the recirculate ventilation setting in high pollution areas and keep their windows closed. However, this setting should only be used for short periods, as extended use can lead to elevated CO_2 levels, which may affect drivers' cognitive performance
- route choice should be carefully considered as avoiding inner-city areas is likely to significantly reduce drivers' exposure. The use of back roads, avoiding tunnels and heavily congested street canyons will also be beneficial
- where using tunnels is necessary, the driver should ensure that windows are closed and ventilation is set to recirculate before entering the tunnel. After exiting the tunnel, the cabin should be well ventilated to reduce the duration of the pollution spike, and recirculate should be switched to the outside air setting to avoid the build-up of CO_2
- where possible, reducing the frequency of driving during the evening peak period (16:00 to 19:00) will decrease drivers' exposures
- moving shifts from weekdays to weekends will also reduce drivers' exposures
- if there are jobs which are likely to cause significantly higher exposure levels (such as work located in heavily congested areas), consideration should be made to rotate drivers in order to avoid any single worker experiencing significantly higher levels of exposure than others
- upgrading fleets to better designed, more airtight cabins will reduce drivers' exposure
- in certain circumstances, in-cabin filters can reduce drivers' exposures. Before introducing these devices to the fleet, companies should first undertake due diligence, assessing the quality of devices and gathering feedback from employees
- employers should conduct training and provide information on diesel exhaust exposure. This should be included in induction and refresher training courses so that the impact of diesel exhaust exposure can be minimised.

While the recommendations in this study identified changes the employer or driver could make, effective policy and regulation would also assist with reducing professional drivers' exposures. A wider and more stringent application of policies to reduce congestion and vehicle emissions would be beneficial. The most effective way to reduce drivers' exposures to diesel exhaust would be to change to zero tailpipe emission vehicles with airtight cabins. This would not only reduce drivers' exposures but would also reduce ambient concentrations, which will in turn provide health benefits for the general population. However, we acknowledge there is both a significant cost and a lack of technology available to do this easily. Consequently, the low-cost changes above are recommended as intermediate steps to immediately reduce diesel exposures to professional drivers.

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Appendix A. Questionnaire provided to participants

PARTICIPANT QUESTIONNAIRE

REC ref: HR-16/17-4415

1. Contact details

Name:	
Job role and employer:	
Email: (optional)	
Mobile: (optional)	

2. Shift details

Please fill out the table or circle answer on each day based on the vehicle you were driving for most of your shift:

	Day 1	**Day 2**	**Day 3**	**Day 4**
Date:				
Shift start time				
Shift end time				
For how many hours of your working day did you drive?				
Vehicle model and fuel (indicate electric or hybrid vehicles)				
Vehicle license plate number				
Did you mostly have a cab window open?	YES / NO	YES / NO	YES / NO	YES / NO

Did you usually switch off your engine when idle?	YES / NO	YES / NO	YES / NO	YES / NO
For most of the day what was the fan / ventilation system on?*	Recirculate/ 'Outside' air / Off	Recirculate/ 'Outside' air / Off	Recirculate / 'Outside' air / Off	Recirculate / 'Outside' air / Off

* Recirculate is typically this icon  in a vehicle

Outside air is typically this icon  in a vehicle

Off is when your fan is set to off or '0' in a vehicle

3. Non-shift details

How did you travel to and from work?...

While carrying the monitor, did you smoke tobacco? Yes [ ] No [ ]

While carrying the monitor were you close to others smoking tobacco?

Yes [ ] No [ ]

If yes to either, were you inside a vehicle while smoking occurred?

Yes [ ] No [ ]

4. Other information

Was there anything unusual about this working period or comments you think relevant? (Such as any noticeable smell or visual signs of air pollution, if so can you please provide date and time)

Thank you

To be completed by researcher:

Date	DEM	Initials
MA serial:	Charger serial:	

Appendix B. Co-location and correction notes for MA300/350

Deming regression was used to obtain correction values for the devices. This technique is commonly used for the correction of air pollution equipment to fixed reference standard monitors. The advantage of using this technique over ordinary least squares regression method is that it takes into account measurement error in both the dependent and independent variables (89). The MicroAeth units had very good correlation with the Marylebone Road monitoring site with slopes ranging between 0.95 to 1.86, intercepts between -1.25 to 0.46 and R^2 between 0.72 to 0.94 (**Table B1**). Co-locations were completed at an hourly resolution. The reference monitor was always set to the x-axis, therefore corrected values were calculated as corrected data = (raw data – intercept)/ slope.

Table B1: Summary of corrections factors calculated for each sensor for co-location campaigns.

Sensor name	Slope	Intercept	R^2
MA300-004	1.13 to 1.25	-0.70 to -0.06	0.82 to 0.83
MA300-005	1.05 to 1.12	-0.50 to -0.02	0.74 to 0.91
MA300-006	1.08 to 1.86	-0.30 to 0.15	0.83 to 0.94
MA300-007	0.98 to 1.44	-0.14 to 0.31	0.84 to 0.94
MA300-008	1.08 to 1.11	-0.02 to 0.38	0.86 to 0.92
MA300-017*	1.16	-0.06	0.72
MA350-001	1.12 to 1.43	-0.40 to 0.16	0.76 to 0.96
MA350-002	1.16 to 1.42	-0.14 to 0.34	0.78 to 0.90
MA350-004	1.06 to 1.75	-1.25 to -0.26	0.75 to 0.83
MA350-005	1.22 to 1.69	-0.21 to 0.38	0.89 to 0.94
MA350-006	0.95 to 1.24	-0.08 to 0.46	0.80 to 0.93

* Only one co-location has been run for this device. However it was only used with three participants

Appendix C. GPS processing and stratification model testing

The first part of GPS processing is to clean the GPS data as GPS signals can get lost or drift in street canyons, buildings or underground[90]. All GPS analyses were conducted in R statistics using libraries 'geosphere', 'lubridate', 'dplyr' and 'zoo'. When the GPS signal was lost, points were interpolated between the last two known points if missing data was less than 120 minutes. If longer than 120 minutes, GPS coordinates were repeated from the last known spot.

The following were calculated from the GPS coordinates for each data point: distance, speed, acceleration and bearing from previous point; rolling 15 minute speed, acceleration and bearing; number of coordinates within 50m, 150m and 250m radius for a rolling 15 minutes; all coordinates by participant within 200m radius (not time limited); consecutive points less than 1.5 m/s (which is a typical walking speed)[90]. This was calculated for both 10 second and one-minute resolution for GPS coordinates. For any speed calculated that was greater than 500 km/hr the GPS coordinates were set to 'NA' and interpolation and recalculation of parameters was rerun.

There are two common techniques in stratifying GPS coordinates into activities: rule- based stratification and machine-learning stratification[63] . Both were tested to see which one could provide the better accuracy in determining whether the participant was driving or not. For the machine-learning based approach only unsupervised learning techniques could be used as validation information on what the drivers were doing at specific time points was not available. Therefore, a hierarchical clustering technique was used set to two clusters (to identify drive and stop activities); this was run with two, eight and all 28 variables.

The rules-based approach reviewed a number of GPS papers[61-64] to provide applicable rules to determine when a participant was driving or stopped. A participant was deemed as stopped where there were more than three consecutive minutes at a speed of less than 1.5 m/s and more than 7 minutes of data points were within a 50m radius for a 15 minute period, or if there was more than 20 per cent of all monitored participants points within a 200m radius (this was to establish participants depot/office and home locations). All other points were deemed as a person driving. The rules were deliberately biased towards stopping to make sure the points that were analysed were actually driving points.

After stratifying GPS points, each participant was visually inspected in the R library 'leaflet' to identify possible errors in stratification. From this visualisation it was determined that the clustering approach was inconsistent and there was less certainty of its accuracy (**Figure C1**). It was also determined that one-minute stratification was more accurate than 10-second stratification due to the propensity for the 10-second data to pick up participants driving in congestion as stop points. Therefore, a rules-based approach was adopted and tested further for its accuracy.

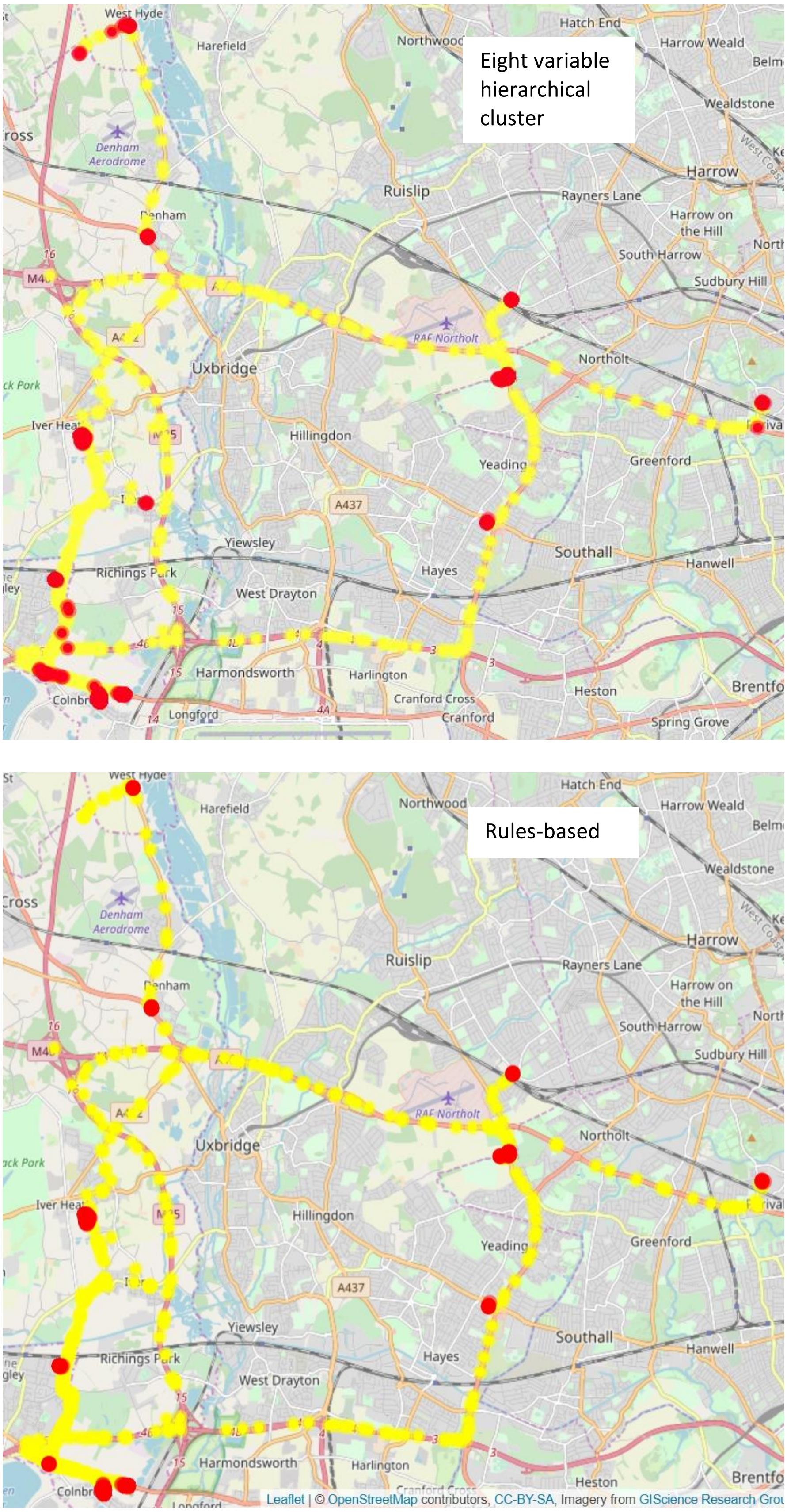

Figure C1: Example of eight variable hierarchical cluster and rules-based cluster on participant DEM078; the red points indicate stops and the yellow points indicate move points.

To test the accuracy of the rules-based model a taxi driver was asked to fill out a manual time activity diary to indicate when they were driving and stopping for six working days 16 and 17 May 2019 and 6 to the 11 June 2019. For the 16 and 17 May 2019, activities were only recorded for work hours; the rules-based approach provided a 96.7 per cent accuracy as shown in the confusion matrix below.

	Actual	
Predicted	Drive	Stop
Drive	696	5
Stop	23	124

Accuracy = (696+124)/ (23+5+696+124) = 96.7%

As this run was only conducted for work hours, most of the time was spent driving. Therefore it is also important to bear in mind that the accuracy, if you decided to classify all points as drive, would be (696+23)/(23+5+696+124) = 84.8 per cent . So, the improvement in the model can be described as 84.8 per cent to 96.7 per cent.

For the period 6 to 11 June 2019, four working days were included (6, 7, 10, 11 June 2019). The accuracy of this model was 98.1 per cent.

	Actual	
Predicted	Drive	Stop
Drive	532	36
Stop	17	2228

Accuracy = (532+2228)/ (36+17+532+2228) = 98.1%

Since this monitor was run for the entire week, most points were classed as stops while the participant was at home, so the accuracy of the model if you decided to classify all points as stop would be 80.4% = (36+2228)/(17+36+532+2228). So, the improvement in the model can be described as 80.4 per cent to 98.1 per cent.

Sensitivities were also calculated by slightly changing the rule parameters to see if the accuracy of the rules-based model could be improved. However, the rules discussed in the section above were determined to be the most accurate to establish correct driving points.

Appendix D. *Post hoc* statistical tests between sectors black carbon exposure

Table D1: Pairwise *post hoc* statistical Dunns tests between sectors BC exposure for all times *'at work'.*

Work	Taxi	Courier	Waste Removal	Heavy Freight	Utility Services	Bus
Courier	0.010*					
Waste Removal	0.004*	0.956				
Heavy Freight	0.002*	1.000	1.000			
Utility Services	0.000*	0.024*	0.022*	0.010*		
Bus	0.000*	0.041*	0.039*	0.020*	1.000	
Emergency Services	0.000*	0.000*	0.000*	0.000*	1.000	1.000

* indicates significance at p <0.05

Table D2: Pairwise *post hoc* statistical Dunns tests between sectors BC exposure for *'at work driving'.*

Driving	Taxi	Courier	Waste Removal	Heavy Freight	Utility Services	Bus
Courier	0.034*					
Waste Removal	0.000*	0.331				
Heavy Freight	0.002*	1.000	0.489			
Utility Services	0.000*	0.299	0.639	0.432		
Bus	0.000*	0.000*	0.093	0.001*	0.454	
Emergency Services	0.000*	0.002*	0.431	0.003*	1.000	0.511

* indicates statistical significance at p <0.05

Table D3: Pairwise *post hoc* statistical Dunns tests between sectors BC exposure for *'at work not driving'.*

Not driving	Taxi	Courier	Waste Removal	Heavy Freight	Utility Services	Bus
Courier	1.000					
Waste Removal	1.000	1.000				
Heavy Freight	0.024*	1.000	0.461			
Utility Services	0.000*	0.000*	0.000*	0.009*		
Bus	0.000*	0.000*	0.000*	0.001*	0.851	
Emergency Services	0.000*	0.000*	0.000*	0.007*	0.968	1.000

* indicates statistical significance at p <0.05

Appendix E. *Post hoc* statistical tests for determinants of black carbon exposure

Table E1: Pairwise *post hoc* statistical Dunns tests for predominant window position while *'at work driving'.*

Windows	Windows open	Windows closed
Windows closed	0.000*	
Not reported	0.333	0.897

Windows adjusted BC	Windows open	Windows closed
Windows closed	0.000*	
Not reported	0.031*	0.079

* indicates statistical significance at p <0.05

Table E2: Pairwise *post hoc* statistical Dunns tests for predominant ventilation settings while *'at work driving'.*

Ventilation	Off	Outside Air	Recirculate
Outside Air	0.957		
Recirculate	0.000*	0.000*	
Not reported	0.002*	0.001*	1.000

Ventilation adjusted BC	Off	Outside Air	Recirculate
Outside Air	0.913		
Recirculate	0.000*	0.000*	
Not reported	0.289	0.363	0.827

* indicates statistical significance at p <0.05

Table E3: Pairwise *post hoc* statistical Dunns tests for smoking status while *'at work driving'.*

Smoker	Non-smoker	Smoker
Smoker	0.000*	
Not reported	0.000*	0.983

Smoker adjusted BC	Non-smoker	Smoker
Smoker	0.000*	
Not reported	0.004*	0.000*

* indicates statistical significance at p <0.05

Table E4: Pairwise *post hoc* statistical Dunns tests for time of day while *'at work driving.*

Time of Day	Morning peak	Day	Afternoon peak
Day	0.000*		
Afternoon peak	0.008*	0.000*	
Night	0.139	0.006*	0.000*

Time of Day adjusted BC	Morning peak	Day	Afternoon peak
Day	0.020*		
Afternoon peak	0.000*	0.000*	
Night	0.071	0.994	0.000*

* indicates statistical significance at p <0.05

Table E5: Pairwise *post hoc* statistical Dunns tests for season while *'at work driving'.*

Season	Spring	Summer	Autumn
Summer	0.000*		
Autumn	0.000*	0.000*	
Winter	0.000*	0.000*	0.000*

Season adjusted BC	Spring	Summer	Autumn
Summer	0.000*		
Autumn	0.000*	0.011	
Winter	0.000*	0.000*	0.000*

* indicates statistical significance at p <0.05

Table E6: Pairwise *post hoc* statistical Dunns tests for location while *'at work driving'.*

Location	Central London	Inner London	Outer London
Inner London	1.000		
Outer London	1.000	0.790	
Outside London	0.000*	0.000*	0.000*

Location adjusted BC	Central London	Inner London	Outer London
Inner London	0.534		
Outer London	0.763	0.809	
Outside London	0.000*	0.000*	0.000*

* indicates statistical significance at p <0.05

Table E7: Pairwise *post hoc* statistical Dunns tests for vehicle type for taxi drivers while *'at work driving'.*

Vehicle Type – Taxi	Mercedez Benz Vito Taxi - Diesel	TX4 Taxi - Diesel
TX4 Taxi - Diesel	0.000*	
TXe Taxi - Hybrid	0.000*	0.000*

Vehicle Type – Taxi adjusted BC	Mercedez Benz Vito Taxi - Diesel	TX4 Taxi - Diesel
TX4 Taxi - Diesel	0.000*	
TXe Taxi - Hybrid	0.000*	0.000*

* indicates statistical significance at p <0.05

Table E8: Pairwise *post hoc* statistical Dunns tests for location while *'at work driving'.*

Vehicle Type – Courier	Ford Transit Van - Diesel	Nissan Voltia - Electric	Vauxhall Vivaro Van - Diesel
Nissan Voltia – Electric	0.263		
Vauxhall Vivaro Van – Diesel	0.000*	0.002*	
Unspecified Van – Diesel	0.342	0.797	0.119

Vehicle Type – Courier adjusted BC	Ford Transit Van - Diesel	Nissan Voltia - Electric	Vauxhall Vivaro Van - Diesel
Nissan Voltia – Electric	0.959		
Vauxhall Vivaro Van – Diesel	0.004*	0.022*	
Unspecified Van – Diesel	0.362	0.445	0.935

* indicates statistical significance at p <0.05

Appendix F. Sensitivity analysis for baseline mixed effects models.

Table F1: Parameters estimate from optimal mixed-effects model to explain determinants of logged *'at work driving'* BC exposures.

Fixed Effect determinants	Categorical Comparison	Estimate	95% CI (lower, upper)	p-Value
(Intercept)		0.74	0.37, 1.12	< 0.0001
Background BC (µg/m^3)		0.15	0.12, 0.18	< 0.0001
Fuel	Electric ~ Diesel	0.04	-0.42, 0.49	ns
	Hybrid ~ Diesel	-0.82	-1.30, -0.34	0.001
Location	Outside ~ Outer London	-0.50	-0.58, -0.41	< 0.0001
	Inner London ~ Outer London	0.13	0.08, 0.19	< 0.0001
	Central London ~ Outer London	0.21	0.14, 0.28	< 0.0001
Time of day	Night time ~ Day time	-0.08	-0.13, -0.02	0.01
	Morning peak ~ Day time	-0.02	-0.06, 0.03	ns
	Evening peak ~ Day time	0.15	0.09, 0.21	< 0.0001
Sector	Courier ~ Bus	0.21	-0.26, 0.68	ns
	Emergency Services ~ Bus	-0.13	-0.53, 0.27	ns
	Heavy Freight ~ Bus	0.02	-0.40, 0.45	ns
	Taxi ~ Bus	0.91	0.46, 1.36	< 0.0001
	Utility Services ~ Bus	-0.08	-0.57, 0.41	ns
	Waste Removal ~ Bus	-0.16	-0.60, 0.27	ns
Smoker Status	Not reported ~ Non-smoker	0.39	0.01, 0.77	0.05
	Smoker ~ Non-smoker	0.35	0.07, 0.63	0.01
Vehicle Speed (km/hr)		0.03	0.02, 0.03	< 0.0001
Day of week	Weekend ~ Weekday	-0.27	-0.35, -0.20	< 0.0001
Predominant window position	Not reported ~ Window closed	0.44	-0.09, 0.97	ns (0.1)
	Windows open ~ Windows closed	0.28	0.20, 0.35	< 0.0001
Wind speed (m/s)		-0.09	-0.11, -0.08	< 0.0001

ns – not significant

The differences between the logged model and the unadjusted optimal model in **section 4.4.8** were that there was a significant negative effect on driver exposure for hybrid compared to diesel vehicles and night time compared to day time, plus a significant positive effect for being a smoker compared to non-smoker.

Appendix G. Sensitivity analysis for intervention mixed effects models.

Table G1: Parameters estimate from optimal intervention mixed-effects model to explain effectiveness of in-cabin filters on 15- minute BC exposures.

Fixed Effect determinants	Categorical Comparison	Estimate	95% CI (lower, upper)	p-Value
(Intercept)		-0.04	-7.44, 7.36	ns
Air temperature (°C)		0.11	0.05, 0.16	0.0004
Background BC (μg/m^3)		1.02	0.73, 1.31	<0.0001
In-cabin filter use	Not reported ~ In-cabin filter not used	0.11	-8.43, 8.64	ns
	In-cabin filter used ~ In-cabin filter not used	0.23	-0.05, 0.51	ns
Fuel type	Hybrid ~ Diesel	-3.54	-9.26, 2.19	ns
Season	Summer ~ Spring	0.29	-6.54, 7.13	ns
Sector	Passenger transport ~ Courier	-0.057	-7.49, 7.38	ns
	Utility services ~ Courier	-0.30	-3.79, 3.20	ns
	Taxi ~ Courier	5.06	-2.64, 12.77	ns
	Waste Removal ~ Courier	0.95	-1.81, 3.72	ns
Smoker Status	Not reported ~ Non-smoker	0.62	-6.75, 8.00	ns
	Smoker ~ Non-smoker	1.39	-1.03, 3.82	ns
Day of week	Weekend ~ Weekday	-10.32	-12.11, -8.53	<0.0001
Predominant window position	Not reported ~ Window closed	0.15	-4.70, 5.01	ns
	Windows open ~ Windows closed	-0.27	-1.40, 0.86	ns
Wind speed (m/s)		-0.21	-0.31, -0.11	<0.0001

ns – not significant

Table G2: Parameters estimate from optimal intervention mixed-effects model removing participants DEM192 and DEM209, to explain effectiveness of in-cabin filters on 15-minute BC exposures

Fixed Effect determinants	Categorical Comparison	Estimate	95% CI (lower, upper)	p-Value
(Intercept)		0.74	-2.89, 4.37	ns
Air temperature (°C)		0.04	0.00, 0.08	ns (0.1)
Background BC (μg/m^3)		0.81	0.60, 1.02	<0.0001
In-cabin filter use	In-cabin filter used ~ In-cabin filter not used	-0.28	-0.48, -0.08	0.006
Fuel type	Hybrid ~ Diesel	-0.21	-2.29, 1.87	ns
Season	Summer ~ Spring	0.59	-2.79, 3.98	ns
Sector	Passenger transport ~ Courier	0.06	-3.47, 3.58	ns
	Utility services ~ Courier	-0.20	-1.57, 1.16	ns
	Taxi ~ Courier	1.13	-2.51, 4.77	ns
	Waste Removal ~ Courier	0.60	-0.45, 1.65	ns
Smoker Status	Smoker ~ Non-smoker	1.27	0.37, 2.18	0.01
Day of week	Weekend ~ Weekday	0.27	-4.42, 4.96	ns
Predominant window position	Windows open ~ Windows closed	0.15	-0.51, 0.81	ns
Wind speed (m/s)		-0.11	-0.18, -0.04	0.004

ns – not significant

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