Assessing the exposure and hazard of diesel exhaust in professional drivers: a review of the current state of knowledge

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Received: 18 December 2020 / Accepted: 19 May 2021 / Published online: 2 June 2021
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Abstract
It is well-established that traffic-related air pollution has a detrimental impact on health. Much of the focus has been on diesel exhaust emissions due to a rapid increase in vehicle numbers and studies finding that this pollutant is carcinogenic. Unsurprisingly, the highest diesel exposures that the general population experiences are during urban daily commutes; however, few studies have considered professional drivers who are chronically exposed to the pollutant due to their work in transport microenvironments. In this narrative review, we address the literature on professional drivers’ exposure to diesel exhaust and advocate that a modern exposure science approach utilised in commuter personal exposure studies is needed. This type of evaluation will provide a more detailed understanding of the time-activity of professional drivers’ exposures which is required to identify specific interventions to reduce their risk to diesel exhaust emissions.

Keywords Diesel exhaust · Occupational drivers · Personal exposures · Black carbon

Introduction
The rapid and sustained growth in vehicle numbers has resulted with engine emissions substantially contributing to urban air pollution issues (Health Effects Institute 2010). This growth has occurred in parallel to an increased appreciation of the health impacts of traffic-related pollutants on human health over the life course. Adverse associations have been observed with birth outcomes (Smith et al. 2017), suboptimal lung (Mudway et al. 2019) and cognitive development (Alvarez-Pedrerol et al. 2017), the development and exacerbation of chronic respiratory (Gehring et al. 2015; Pfeffer et al. 2018; Samoli et al. 2016) and cardiovascular disease (Alexeeff et al. 2018; Atkinson et al. 2010; Bell et al. 2014), increased risk of dementia (Carey et al. 2016) and cancer (Hart et al. 2015) and ultimately premature death (Atkinson et al. 2016; Hoek et al. 2002).

Alongside traffic-related air pollution, the increase in vehicle numbers has also led to concerns over their contribution to global warming, leading the European Commission in the 1990s to incentivise diesel vehicles due to their lower carbon dioxide emissions compared to gasoline vehicles (Cames and Helmers 2013). As a result, in the last 20 years, there has been an increase of 45 million diesel cars in Europe (Cames and Helmers 2013), with diesel vehicles increasing from 27.1% in 2005 to comprise 42.4% of the European vehicle fleet by 2017 (European Environment Agency 2018). Whilst they do emit less carbon dioxide, the increase in diesel vehicles has led to the concern that they are disproportionately adding to the air pollution health burden. Regulators have found they emit significantly higher levels of fine particulate matter compared to gasoline vehicles, with estimates that diesel vehicles contribute greater than 90% of total exhaust emissions in the UK (Monks et al. 2012).

Whilst the health effects of traffic-related pollution are now well-established, studies have identified that exposure to diesel exhaust is highest for the general population during the daily commute (Karana siou et al. 2014). However, few studies
have considered professional drivers who are chronically exposed to the pollutant due to their prolonged work in transport microenvironments (Knibs and Morawska 2012). This paper reviews our current knowledge on the hazard and exposure of diesel exhaust in professional drivers. We briefly outline methods employed which identified the health risks of diesel exhaust emissions and provide a narrative review on studies which have measured professional drivers’ occupational exposure to diesel exhaust. The paper concludes by highlighting how a modern exposure science approach utilised in commuter studies can enhance our understanding of professional drivers’ risk of diesel exhaust exposure and assist in identifying strategies to reduce adverse health outcomes in this occupation.

Assessing the health effects of diesel exhaust emissions

The evidence of the health effects of traffic-related pollution was initially identified by assessing health metrics of populations who live nearby to heavy traffic. These studies have found increased cardiopulmonary mortality, asthma and reduced lung function for those living near major roads (Brunekreef et al. 2009; Health Effects Institute 2010; Hoek et al. 2002; Janssen et al. 2003), with one study finding that an increase in diesel truck traffic resulted in an exacerbation of asthma symptoms (Brunekreef et al. 2009). More recently, studies addressing the impact of traffic-related air pollution on health, link health data to estimates of individual exposures within the population, with nitrogen dioxide (NO2) most often used as a proxy for traffic-related pollution (Atkinson et al. 2016; Samoli et al. 2016).

Increasingly, there has been focus on the measurement of primary combustion particles from the tailpipe of vehicles, using a variety of metrics such as black carbon (BC), elemental carbon (EC) or particle number concentrations. Concentrations of these traffic-derived pollutants have been measured at urban background sites in major cities and then related to daily variations in deaths and hospital admissions (Atkinson et al. 2016; Samoli et al. 2016), and models have been developed to estimate individual exposures in more spatial detail, both in Europe and North America (de Hoogh et al. 2018; Jones et al. 2020). Those studies that have compared the impacts of total ambient PM mass against these refined estimates of tailpipe exposure have generally found the latter to be more strongly associated with adverse health effects (Atkinson et al. 2016; Janssen et al. 2011; Samoli et al. 2016), with diesel exhaust emissions thought to contribute disproportionately to these pollutant concentrations (Janssen et al. 2011).

The statistical associations observed between traffic-derived air pollution and adverse health effects are also supported by experimental studies in which human volunteers have been exposed to diesel exhaust under controlled conditions. These studies have demonstrated the induction of acute pulmonary and systemic inflammation (Salvi et al. 1999), as well as cardiovascular effects (Mills et al. 2007) using diluted exhaust from engines operating under idling and loaded conditions (Barath et al. 2010).

The health studies reported are often criticised due to uncertainty around whether the proxy values or controlled concentrations used are an accurate surrogate for actual exposure (Brauer et al. 2002). Exposure misclassification is the difference between estimated exposure (through fixed monitors or models) and an individuals’ true exposure (Health Effects Institute 2010). It is thought that exposure misclassification is higher for those populations that have disproportionately higher exposure (Health Effects Institute 2010) such as those living, working or going to school near busy roads, or those who work in highly polluted environments such as professional drivers. Personal monitoring, where participants carry a portable monitor to assess how much air pollution they inhale as they go about their typical day is often viewed as the gold standard for exposure assessment (Brokamp et al. 2019; Health Effects Institute 2010). This type of monitoring is utilised to reduce exposure misclassification and provide better dose exposure response estimates. Several studies have utilised personal monitoring for short time periods (typically over 1–2 h) and examined the responses of individuals, both healthy and with pre-existing disease (asthma, chronic obstructive lung disease, ischaemic heart disease, etc.) to real-world exposures in high diesel vehicle microenvironments (McCranor et al. 2007; Sinharay et al. 2018). These studies have also shown impacts on lung function, airway inflammation and vascular indices (McCranor et al. 2007; Sinharay et al. 2018).

Personal monitoring was initially conducted to better characterise occupational exposures, associated health risks and to provide better working conditions for employees. Occupations where diesel emissions are prevalent have been scrutinised with studies finding excess lung cancer deaths associated with exposure to EC in miners (Silverman et al. 2012) and truck workers in the USA (Garshick et al. 2012). Diesel engine exhaust was also estimated to be the third most harmful substance (after asbestos and silica) related to occupational lung cancer in the UK (Rushton et al. 2012). These studies contributed to diesel exhaust being classified as a class 1 carcinogen (International Agency for Research on Cancer 2012), and is therefore a known occupational risk to individuals who are chronically exposed to this pollutant including professional drivers. Whilst there are known health effects, there is minimal evidence in published literature as to what can be done to reduce drivers’ exposure to diesel emissions.
Studying diesel exposures in the real world

Ambient air pollution represents a heterogenous mixture of particles and gases, derived from mixed sources. To assess the contribution of diesel engine exhaust to this mixture requires the use of surrogate measures, where the contribution of diesel is greater than that of other mixed sources. Recent studies have moved toward the measurement of BC or EC as a proxy for diesel emissions (Janssen et al. 2011; Samoli et al. 2016).

Although BC and EC both represent the carbonaceous aerosol, they represent slightly different properties of particulate matter, with BC described as a light absorbing substance composed of carbon and EC as the carbonaceous fraction that is thermally stable in an inert atmosphere (Petzold et al. 2013). In practice, they largely differ only in their measurement technique, where EC is based on thermal-optical methods, whilst BC by optical absorption methods (Briggs and Long 2016). Despite this difference, in locations where the primary source of carbonaceous aerosol is diesel exhaust they are highly correlated (Hessey et al. 2017; Salako et al. 2012). This is particularly relevant in Europe and North America as 70% of emissions of BC are estimated to be from diesel engines (Bond et al. 2013). EC is often measured in occupational studies as a marker of diesel engine exhaust due to approved measurement methods from NIOSH (National Institute for Occupational Safety and Health 1994); however, given the high correlation, we suggest that BC should also be accepted in occupational exposure assessment of diesel exposure as well. This is primarily due to the differences in measurement technique with EC required to be measured on filters making high time-resolved measurements difficult. BC can be measured at resolutions as low as one second (Cheng and Lin 2013), and this can provide an improved understanding on the causes of high exposure during a working day and a better tool with which to manage at-risk populations to diesel exposure. There is also growing interest in employing BC for regulatory air quality assessments, with reports from the World Health Organisation (2012), US Environment Protection Agency (2012) and European Environment Agency (2013) all emphasising the burden associated with this pollutant metric on human health.

Professional drivers and occupational exposure to diesel exhaust

It has been acknowledged in a number of studies that the urban commuting microenvironment most intensely contributes to people’s daily air pollution exposure (Dons et al. 2011; Karanasiou et al. 2014; Lim et al. 2015). Studies have also found that although people typically spend only 6–10% of their day in the commute environment, this contributes between 20 and 30% of their daily exposure (Dons et al. 2012; Williams and Knibbs 2016). The average exposure during commuting has been found to be up to eight times higher than in the home environment (Dons et al. 2011).

However, most of these studies focus on in-vehicle exposures in individuals during their daily commute to and from a fixed place of work. In comparison, there has been a relative absence of studies addressing the occupational exposures of urban professional drivers to air pollution (Gany et al. 2017; Knibbs and Moraw ska 2012). Whilst typically the commute for the majority of workers only takes up to a couple of hours each day, those employed to drive as part of their job such as couriers, bus drivers, taxi drivers, waste removal, emergency service workers and other such occupations can spend up to 12 h of their day in urban transport microenvironments. One study that investigated occupational exposures found that truck drivers in a high polluted urban environment in Beijing had over a third higher exposure to EC compared to office workers (Baccarelli et al. 2014), supporting the view that professional drivers are likely exposed to far higher concentrations of traffic-related air pollutants than typical office workers. It is therefore highly likely that individuals who are in-vehicles for most of their working day are disproportionately affected by air pollution.

Current occupational epidemiological studies have been criticised for the use of imprecise proxies for diesel exposure, with occupational mortality often linked to years in job or against workers in non-exposed occupations (Fang et al. 2010; Sun et al. 2014). There have been reviews investigating the health effects of ambient pollution to commercial drivers (Lawin et al. 2018), biomarkers of occupational exposure (Brucker et al. 2020) and occupational exposures to diesel exhaust (Prnk et al. 2009). However, none have identified studies investigating where and when the highest exposures for professional drivers occur and how these exposures could be mitigated. Here, we summarise occupational professional driver exposure studies to BC and EC conducted between 2000 and 2020. An electronic search was conducted in PubMed using the terms “drivers”, “occupational”, “diesel”, “black carbon”, “elemental carbon” and “exposure”. Studies were included if they physically measured personal exposure for professional drivers and were observational. No experimental or intervention studies were included.

We identified 16 studies which measured personal professional drivers’ exposure (Table 1). Average shift exposures ranged from 1 to 64 μg/m³ for EC and BC. Seven studies were conducted in Asia, four in North America, four in Europe and one in Africa. The highest exposures were measured in Africa (64 μg/m³) and Asia (4 to 28 μg/m³). Unlike the European and North American studies, there is uncertainty around whether the high exposures in African and Asian countries predominantly relate to diesel emissions, due to other sources of EC and BC in these countries such as biomass burning (Salako et al. 2012). The highest exposure recorded in high-income countries was 10 μg/m³ in Estonia in 2002. The
lowest exposures were found in all four studies in the USA (1 to 3 μg/m³), which is not surprising given the comparatively low proportion of diesel vehicles in the country (Chambers and Schmitt 2015). It is important to note that a number of these studies were conducted over 10 years ago, and since this time regulations for new vehicles have decreased tailpipe emissions by up to 90% particularly in European and North American locations (Anenberg et al. 2017; Fiebig et al. 2014). Despite more stringent emission regulations, the latest studies in 2017 and 2019 on taxi drivers in Europe found exposure to EC and BC between 3 and 9 μg/m³ (Hachem et al. 2021; Moreno et al. 2019). This is a concern as a study found that a lifetime occupational exposure of 1 μg/m³ of EC would lead to 17 excess lung cancer deaths per 10,000 individuals, above agreed occupational risk limits in the USA and Europe (Vermeulen et al. 2014).

Only two of the studies reviewed (Baccarelli et al. 2014; Davis et al. 2007) sampled more than 80 shifts with the majority less than 20 and focussed on a single sector such as taxi, bus or truck drivers, making it difficult to assess whether these studies are representative of the industry as a whole. Only five out of the 16 studies employed time-resolved instrumentation (Gany et al. 2017; Hachem et al. 2020, 2021; Lee et al. 2015; Moreno et al. 2019) using a portable aethalometer to measure BC at a 1-min time resolution. All other studies used time-integrated assessment for the duration of the drivers shift or for one study over a 24-h period. The issue with the time-integrated studies is that they cannot provide time or location specific information on where the driver experienced most of their exposure and hence it is difficult to provide advice on interventions and encourage behaviour change to reduce their exposure. Of the five high time-resolved studies, 17 waste truck workers had their personal BC exposure measured in a study in Seoul, Korea (Lee et al. 2015); with the study reporting that better engine emission standards, lower tonnage and placement of tail pipes had a significant influence on the workers exposure, highlighting some potential interventions which could reduce occupational exposures. The second study in New York City measured BC and PM$_{2.5}$ exposures to seven taxi cab drivers and found that in-vehicle exposures were almost double those of background monitors (Gany et al. 2017). The three other studies measured 20 taxi driver shifts in Lebanon (Hachem et al. 2020), 14 taxi driver shifts in Barcelona (Moreno et al. 2019) and 50 taxi driver shifts in Paris (Hachem et al. 2021) and suggested that drivers’ BC exposure was affected by meteorology, vehicle type, window position and ventilation settings. Whilst these studies help illustrate the high exposures of drivers, the sample sizes are small and variations in design and monitoring make an integrative summary difficult. Utilising time-resolved monitors alongside GPS devices can also assist in identifying locations and times where the highest exposure occurs and provide better information to assist drivers, employers and regulators to reduce diesel exposure in this occupation. This is particularly important for professional drivers, as unlike most other occupations they move across large distances and through heterogenous locations.

As an illustration of this point, we have included some representative BC exposure data collected from a taxi driver in London, across a single shift (Fig. 1). This highlights several key points: (1) the extremely high peak exposures occurring when travelling through the most congested parts of the city (> 90 μg/m³); (2) the extended duration of in-vehicle peak concentrations (in this instance this lasts over 30 min); (3) the independence of the in-vehicle exposures from stationary roadside BC measurement over the same period; and (4) the very high proportion of BC exposure experienced during work, versus time spent at the office or at home. This short example provides an insight into the type of information that is lacking in most studies, but which would improve our understanding of professional drivers’ exposures to diesel exhaust.

**Fig. 1** Representative black carbon concentrations measured by a taxi driver working in London. The upper panel illustrates in-vehicle black carbon exposure during a journey from west (Heathrow) to east (Bethnal Green) London, starting at 18:10, 20 April 2018, with a peak measured concentration > 90 μg/m³. The lower two panels show the real-time measurements of black carbon between 14:00 and 00:00, including the journey illustrated in the upper panel, at 1 and 15-min resolution. The personal exposure for the taxi driver within the office and home environment are also marked for comparison. In the lower panel, roadside black carbon concentrations measured at a London roadside site are illustrated to show the potential mismatch between population exposures at a fixed roadside monitor and within vehicles in the congested urban environment.
Table 1  Summary of occupational exposure measurements for professional drivers to black carbon (BC) and elemental carbon (EC) since 2000, ordered from highest measured exposure to lowest

| Author          | Year and season of data collection | Location               | Monitor                        | Occupation      | Pollutant | Mean exposure ($\mu$g/m$^3$) (GM = geometric mean, M = Median) | Standard deviation ($\mu$g/m$^3$) (GSD = geometric SD) | Shifts monitored | Time monitored (h) | Time resolution of monitor |
|-----------------|------------------------------------|-------------------------|--------------------------------|-----------------|-----------|---------------------------------------------------------------|---------------------------------------------------------------|-----------------|----------------------|--------------------------|
| Ngo et al. 2015 | Dry season, 2011                  | Nairobi, Kenya          | BGI sampler, teflon filter     | Bus drivers     | BC        | 63.9 (18.6)                                                   | 7 (8)                                                       | Duration of shift |
| Jinsart et al. 2012 | Dry season 2009                  | Bangkok, Thailand       | Sibata pump, quartz filter     | Bus, taxi and tuk tuk drivers | EC      | 31 (10)                                                       | 32 (6)                                                      | Duration of shift |
| Jinsart et al. 2012 | Rainy season 2008                 | Bangkok, Thailand       | Sibata pump, quartz filter     | Bus, taxi and tuk tuk drivers | EC      | 28 (10)                                                       | 37 (6)                                                      | Duration of shift |
| Miller-Schulze et al. 2010 | Summer, 2007                 | Shenyang, China          | Sibata pump, quartz filter     | Taxi drivers    | EC        | 25.7 (5.6)                                                   | 23 (8 - 10)                                                  | Duration of shift |
| Baccarelli et al. 2014 | Summer, 2008                        | Beijing, China          | Apex pump, teflon filter       | Truck drivers   | EC        | 17.3 (6.7)                                                   | 120 (8)                                                     | Duration of shift |
| Du et al. 2011 | Autumn, 2006                      | Beijing, China          | SKC pump, teflon filter        | Taxi drivers    | BC        | 15.4 (6.0)                                                   | 20 (24)                                                     | Full day |
| Lee et al. 2015a | Summer, 2014                     | Seoul, South Korea      | MicroAetholometer AE 51, Aethlabs | Waste removal workers | BC      | 9.6 (3.5)                                                   | 17 (8)                                                      | 1 min |
| Boffeta et al. 2002 | 2002                               | Estonia                 | IOM sampler and quartz filter | Bus drivers     | EC        | 9.5 (2.1)                                                   | 5 (6.5)                                                     | Duration of shift |
| Moreno et al. 2019 | Autumn, 2017                        | Barcelona, Spain        | Personal environmental monitor, quartz filter | Taxi drivers | EC        | 9.4 (M)                                                       | 14 (6)                                                      | Duration of shift |
| Lewne et al. 2007 | 2002–2004                          | Stockholm, Sweden       | Pump and quartz filter         | Taxi drivers    | EC        | 6.7 (GM) (1.6 (GSD))                                         | 4 (~ 16)                                                    | Duration of shift |
| Moreno et al. 2019a | Autumn, 2017                        | Barcelona, Spain        | Mini-aethalometer (Magee Scientific) | Taxi drivers | EC        | 6.5 (M)                                                      | 14 (6)                                                      | 10 s |
| Lewne et al. 2007 | 2002–2004                          | Stockholm, Sweden       | Pump and quartz filter         | Taxi drivers    | EC        | 6.4 (GM) (2.9 (GSD))                                         | 10 (~ 16)                                                   | Duration of shift |
| Lee et al. 2015 | Summer, 2014                      | Seoul, South Korea      | MSA pump, quartz filter        | Waste removal workers | BC      | 5.8 (4.8)                                                   | 72 (8)                                                      | Duration of shift |
| Hachem et al. 2020a | Summer, 2019                        | Beirut, Lebanon         | MicroAetholometer AE 51, Aethlabs | Taxi drivers | BC      | 5.2 (1.9)                                                   | 20 (5)                                                      | 1 min |
| Wu et al. 2011 | Summer 2008                        | Beijing, China          | SKC pump, quartz filter        | Taxi drivers    | EC        | 4.2 (M)                                                       | 48 (12)                                                     | Duration of shift |
| B. K. Lee et al. 2005 | 2003                              | Detroit, US             | BGI sampler, teflon filter     | Truck drivers   | EC        | 3.1 (4.0)                                                   | 32 (8–12)                                                   | Duration of shift |
| Hachem et al. 2021a | 2019                               | Paris, France           | MicroAetholometer AE 51, Aethlabs | Taxi drivers | BC      | 2.9 (M)                                                      | 50 (~ 10)                                                   | 1 min |
| Gany et al. 2017a | Winter 2012–2013                  | New York City, US       | MicroAetholometer AE 51, Aethlabs | Taxi drivers | BC      | 2.4 (0.6)                                                   | 7 (6–12)                                                    | 1 min |
| Ramachandran et al. 2005 | 2005                          | Minneapolis, US         | MSA pump, quartz filter        | Bus drivers     | EC        | 2.0 (1.3)                                                   | 39 (6.3)                                                     | Duration of shift |
| Davis et al. 2007 | 2001–2005                         | 36 locations in US      | BGI sampler, teflon filter     | Local pickup and delivery truck drivers | EC      | 1.6 (2.3)                                                   | 576 (~ 10.5)                                                | Duration of shift |
| Davis et al. 2007 | 2001–2005                         | 36 locations in US      | BGI sampler, teflon filter     | Long haul truck drivers | EC      | 1.4 (0.8)                                                   | 349 (~ 10.5)                                                | Duration of shift |

*a* Indicate studies monitoring with time-resolved methods whilst all other studies used time-integrated methods.
2013), the number of commuting exposure studies focussing on diesel emissions in the last 10 years has rapidly increased. An electronic search was therefore conducted in PubMed using a combination of these terms “black carbon”, “elemental carbon”, “diesel”, “exposure”, “vehicle”, “commute” for studies between 2000 and 2020. We provide a broad review of these commuter exposure papers to identify insights which can be employed to enhance occupational assessments and improve our understanding of professional driver exposure to diesel exhaust.

We identified 27 studies measuring in-vehicle exposure to BC and EC (Table 2); the studies were restricted to vehicles which professional drivers were likely to drive such as cars, buses and vans and excluded any modelled exposures. Twenty-five of the studies measured commuting exposure at high time resolution, with some studies measuring exposures at a 1-s resolution. There was a significant variation between studies with in-vehicle BC exposure ranging from 0.5 to 77.5 μg/m³ across 16 countries. This is likely due to a number of reasons including differences in location (meteorology, traffic characteristics, levels of congestion), duration, study design (averaging time, replications, ventilation settings) and vehicle type and age.

These studies are unlikely to represent professional drivers’ exposures, as they largely focused on short commutes in morning and evening rush hours on fixed routes with the researcher simulating expected commuter behaviour. However, insights on the determinants of commuters’ exposures could be similar for professional drivers and should be further investigated. Determinants of personal exposure in transport are typically grouped in four ways, personal factors, mode of transport (bus, train, bicycle, walk, car, etc.), traffic factors and meteorology (Kaur et al. 2007). In-vehicle exposure can be highly variable in time and space due to meteorology, season, fuel type, ventilation settings, traffic levels, filters, driver behaviour, proximity to pollution source, dispersion of emissions in roads and street canyons (determined by wind speed and direction, turbulence and boundary layer factors), air tightness of vehicle, vehicle age, type of vehicle and other vehicle characteristics (Dons et al. 2013; Ham et al. 2017; Karanasiou et al. 2014; Li et al. 2015; Tartakovsky et al. 2013) (Fig. 2).

Studies have found a high variability of in-vehicle traffic-related pollutant concentrations depending on street type and density of vehicles (Li et al. 2015). Intersections and highways have been found in previous studies to have the highest in-cabin exposure levels for BC (Dons et al. 2013), with heavy-duty diesel vehicles thought to be the highest contributor to exposure (Li et al. 2015). Peak hours have also been associated with the highest exposure, with congestion thought to be the main contributor for elevated in-vehicle exposure (Dons et al. 2013; Good et al. 2016; Zurbvier et al. 2010).

Micrometeorology within street canyons or tunnels could also be of influence, as this can cause high accumulation of pollutants in localized areas (Vardoulakis et al. 2003), leading to infiltration into vehicles.

Studies have found that ventilation settings in vehicles can reduce exposure by up to 75% (Ham et al. 2017). With having the windows open being the worst way to ventilate your vehicle compared to other ventilation modes such as outside air and recirculate modes (Li et al. 2015; Okokon et al. 2017; Williams and Knibbs 2016). However, even when windows are open, and are subsequently closed and recirculate mode is employed, this can lead to a drastic reduction in BC, suggesting that pollutants can be efficiently removed from the cabin (Li et al. 2015). Other ways to reduce in-vehicle exposure are to install filters or air purifiers on the ventilation system, with one study finding that purifiers reduced fine particle concentrations by up to 99% compared to the outside air (Tartakovsky et al. 2013). The air tightness of the vehicle 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 (Bos et al. 2021; Karanasiou et al. 2014).

There is insufficient evidence to suggest whether in-vehicle exposure is affected by different vehicle types and fuel. There is further uncertainty on the effect of self-pollution in-vehicles; however, one study has found that self-pollution can contribute up to 30% of PM2.5 exposure experienced by car occupants (Harik et al. 2017), potentially indicating higher exposure to drivers of diesel cars. Self-pollution in buses has also been suggested due to the frequency of door opening and exhaust location with newer bus fleets having lower in-cabin concentrations compared to older fleets (F. Yang et al. 2015; Zhang and Zhu 2010; Zurbvier et al. 2010). Despite a number of studies investigating the determinants of in-vehicle exposures, there is still significant difficulty in identifying which variables should be prioritised to reduce exposure.

This evidence suggests that there may be practical behaviour changes, new technology and different cabin types that can reduce exposures to professional drivers; however, we did not identify any studies that tested this hypothesis in a real-world setting. There is uncertainty whether similar interventions for this occupation would be effective in reducing exposures as their activity is likely to be substantially different to the everyday commuter. Furthermore, whilst these commuter studies focus on driving exposures, it is unknown whether exposures would also be high for professional drivers when they are working but not driving, separating these microenvironments throughout the working day will also be an important facet for accurate exposure assessment in this occupation.
Table 2  Summary of in-vehicle black carbon and elemental carbon measurement studies since 2000

| Author                  | Year and season of data collection | Type                  | Location | Equipment                              | Vehicle type and setting                      | Mean exposure (µg/m³) (GM = Geometric Mean, M = Median) | Std Dev (µg/m³) (GSD = Geometric Std Dev, R = Range) | Number of trips | Time of trip (min) | Time resolution of monitor (s) |
|-------------------------|-----------------------------------|-----------------------|----------|----------------------------------------|-----------------------------------------------|-----------------------------------------------------|-------------------------------------------------|----------------|-------------------|--------------------------|
| Adams et al. 2002       | Summer, 1999, Winter, 2000       | Fixed route           | London, UK | Pump and Teflon Filters                | Car (Summer), Bus (Summer), Car (Winter), Bus (Winter) | 21.6 (GM), 13.6 (GM), 27.3 (GM), 18.6 (GM)           | 2.1 (GSD), 1.9 (GSD), 2.0 (GSD), 2.3 (GSD)       | 15             | 16 to 59          | Duration of trip          |
| Adar et al. 2007         | Spring 2002                      | Fixed route           | St Louis, US | Magee Scientific Aethalometer MicroAetholometer AE 51, Aethlabs | Auto Rickshaw, Car Tata Indica, Car Tata Indica | 43.0, 49.0, 29.0                                     | –, –, –                                      | –              | 47               | 180, 60          |
| Apte et al. 2011         | Spring, Summer 2010              | Fixed route           | New Dehli, India | MicroAetholometer AE 51, Aethlabs | Auto Rickshaw, Car Tata Indica, Car Tata Indica | 43.0, 49.0, 29.0                                     | –, –, –                                      | –              | 5                | 10                       |
| de Nazelle et al. 2012   | Summer, 2009                     | Fixed route           | Barcelona, Spain | MicroAetholometer AE 51, Aethlabs | 2008 Renault Clio diesel bus, Caprice Sedan | 19.5, 16.1                                         | 1.8 (GSD), 1.5 (GSD)                           | 36             | 120              | 1                       |
| Dons et al. 2012         | Winter, 2010–2011                | Uncontrolled          | Flanders, Belgium | MicroAetholometer AE 51, Aethlabs | Car drive, Car passenger, Bus Passenger | 7.6, 6.4, 6.6                                       | –, –, –                                      | –              | Not reported       | Not reported            |
| Fruin et al. 2004        | Autumn, 1997                     | Fixed route           | Los Angeles, US, Sacramento, US | AE16 Aethalometer, Magee | 1991 Chevrolet Caprice, 2005 Ford Taurus | 16, 9                                               | 16, 11                                        | 16             | 120              | 60                       |
| Ham et al. 2017          | 2014–2015                        | Uncontrolled          | Seoul, Korea | MicroAetholometer AE 51, Aethlabs | Private Vehicle | All, Outside air, Windows Open | 0.5, 0.4, 0.6, 0.3, 0.4, 0.6, 0.4, 0.3 | 101, 22, 22, 10, Not reported, Not reported, Not reported | Unknown, Unknown | 300              | 1688                     |
| Jeong and Park 2017      | Summer-Winter 2015–2016          | Uncontrolled          | Seoul, Korea | MicroAetholometer AE 51, Aethlabs | Car, taxi and motorcycle, Van and Minibus | 4.2, 7.5                                           | 2.7, 9.5                                     | Unknown        | Unknown           | 300                       |
| Lee et al. 2010          | Spring, 2007                     | Fixed route           | Lexington, US | MicroAetholometer AE 51, Aethlabs | 2005 Ford Taurus | Car | Windows closed, Windows open | 1.5 to 2.5, 8.6, 11.8, 7.3, 5.5 | –, 12, 12, 12 | 39, 60, 30 | 60, 40 - 160, 30 |
| Lei et al. 2017          | Autumn, 2015                     | Fixed route           | Shanghai, China | MicroAetholometer AE 51, Aethlabs | Car, Taxi Bus, Car/Taxi, BRT-Bus | 41.0 (M), 77.5 (M)                                  | 2.9 (GSD), 2.8 (GSD)                            | 6, 20            | 12, 90          | 30, 15                   |
| Li et al. 2015           | Summer, 2014                     | Fixed route           | Shanghai, China | MicroAetholometer AE 51, Aethlabs | Car, Taxi Bus, Car/Taxi, BRT-Bus | 41.0 (M), 77.5 (M)                                  | 2.9 (GSD), 2.8 (GSD)                            | 6, 20            | 12, 90          | 30, 15                   |
| Morales Betancourt et al. 2017 | Dry season 2015            | Fixed route           | Bogota, Colombia | MicroAetholometer AE 51, Aethlabs | Euro 2 or 3 Bus | Unknown | 5.5, 5.5, 5.5, 5.5, 5.5 | 3.6, 3.6, 3.6, 3.6, 3.6 | Not reported, Not reported, Not reported, Not reported, Not reported | Unknown, Unknown | 300              | 1688                     |
Table 2 (continued)

| Author          | Year and season of data collection | Type         | Location                  | Equipment                  | Vehicle type                  | Ventilation Settings | Mean exposure (μg/m³) (GM = Geometric Mean, M= Median) | Std Dev (μg/m³) (GSD = Geometric Std Dev, R= Range) | Number of trips | Time of trip (min) | Time resolution of monitor (s) |
|-----------------|------------------------------------|--------------|---------------------------|----------------------------|------------------------------|----------------------|--------------------------------------------------------|---------------------------------------------------|----------------|-------------------|--------------------------|
| Merritt et al. 2019 | 2013                              | Fixed route  | Stockholm, Sweden         | MicroAetholometer AE 51, Aethlabs | 2012 Volvo C50 hybrid Bus      | Closed Windows          | 2.0                                                    | 0.0 to 19.0 (R)                                           | 663            | ~ 7               | 60                       |
| Okokon et al. 2017   | Spring, 2011                       | Fixed route  | Helsinki, Finland         | MicroAetholometer AE 51, Aethlabs | Ford Focus Wagon (2008-2010) | Open Windows           | 2.7                                                    | 0.2 to 37.2 (R)                                           | 1251           | ~ 11              | 60                       |
|                    |                                     |              |                           |                            |                              |                       | 7.8                                                    | 4.3                                                          | 6              | 20                | 60                       |
|                    |                                     |              |                           |                            |                              |                       | 2.8                                                    | 2.3                                                          | 6              | 20                | 60                       |
|                    |                                     |              |                           |                            |                              |                       | 4.6                                                    | 4.4                                                          | 6              | 23                | 60                       |
|                    |                                     |              | Rotterdam, Netherlands    |                            |                              | Open Windows            | 6.4                                                    | 3.3                                                          | 6              | 23                | 60                       |
|                    |                                     |              |                           |                            |                              |       | 6.3                                                    | 3.4                                                          | 6              | 23                | 60                       |
|                    |                                     |              |                           |                            |                              |       | 4.3                                                    | 2.6                                                          | 6              | 27                | 60                       |
|                    |                                     |              |                           |                            |                              |       | 10.9                                                   | 9.9                                                          | 6              | 21                | 60                       |
|                    |                                     |              |                           |                            |                              |       | 4.7                                                    | 3.4                                                          | 6              | 21                | 60                       |
| Pant et al. 2017    | 2014–2016                          | Fixed route  | New Dehi, India           | MicroAetholometer AE 51, Aethlabs | Bus            | Unknown                   | 8.5                                                    | 5.1                                                          | 6              | 32                | Unknown 60               |
| Patton et al. 2016  | 2007–2014                          | Fixed route  | New Jersey Turnpike, US   | MicroAetholometer AE 51, Aethlabs | Varied Cars     | Windows closed, outside air | 4.0 (M)                                                   | -                                                          | 190            | Unknown 1         | 60                       |
| Rivas et al. 2017   | Spring, 2016                       | Fixed route  | London, UK                | MicroAetholometer AE 51, Aethlabs | Petrol Peugeot 208 Active 1.2 | Windows closed and recirculate | 4.4 (GM)                                                   | 2.5 (GSD)                                                | 90              | 49 to 66          | 10                       |
| Sarnat et al. 2014  | 2009 - 2011                        | Fixed route  | Atlanta, US               | MicroAetholometer AE 51, Aethlabs | Bus            | Unknown                   | 5.4 (GM)                                                   | 2.3 (GSD)                                                | 47              | 33                | 78 120 Not reported    |
| Targino et al. 2018 | Autumn 2014                        | Fixed route  | Londrina, Brazil          | MicroAetholometer AE 51, Aethlabs | Unspecified Bus | Mixed                    | 9.6                                                    | 12.2                                                        | 8              | 120               | Not reported             |
| Tan et al. 2017     | Dry season 2013                     | Fixed route  | Singapore                 | MicroAetholometer AE 51, Aethlabs | Taxi           | Windows closed and recirculate | 2.9 (GM)                                                   | 3.9 (GSD)                                                | 23              | 8                | 1                       |
| Vouitis et al. 2014 | Spring 2011                        | Fixed route  | Thessaloniki, Greece      | MicroAetholometer AE 51, Aethlabs | Bus            | Unknown                   | 3.2 (GM)                                                   | 3.3 (GSD)                                                | 23              | 7                | 24                       |
| Author                  | Year and season of data collection | Type               | Location                  | Equipment                                      | Vehicle type                        | Ventilation Settings | Mean exposure (μg/m³) (GM = Geometric Mean, M = Median) | Std Dev (μg/m³) (GSD = Geometric Std Dev, R = Range) | Number of trips | Time of trip (min) | Time resolution of monitor (s) |
|------------------------|-----------------------------------|--------------------|---------------------------|-----------------------------------------------|-------------------------------------|----------------------|---------------------------------------------------------|--------------------------------------------------------|----------------|---------------------|-----------------------------|
| Wagon Petrol           | 2008-2010 Ford Focus Wagon Petrol | Windows closed     | 4.2                       | 2.8                                           | 12                                  | ~ 21                 |
| Weichenthal et al. 2015| Summer and Winter, 2010           | Fixed route        | Toronto, Canada           | MicroAetholometer AE 51, Aethlabs             | Chevrolet Grand Caravans 2009–2012 | Windows Closed       | 7.4                                                      | 3.1                                                    | 67             | 180                 | 1                          |
|                       | Winter, 2012 and Summer, 2013     |                    | Vancouver, Canada         |                                                | Chevrolet Grand Caravans 2009–2012 | Windows Closed       | 2.0 (M)                                                 | 0.2 to 7.3 (R)                                         | 113            | 180                 |                            |
|                       | Winter 2011                       |                    | Montreal, Canada          |                                                | Chevrolet Grand Caravans 2009–2012 | Windows Closed       | 1.5 (M)                                                 | 0.4 to 2.7 (R)                                         | 14             | 180                 |                            |
| Williams and Knibbs 2016| Not reported                      | Uncontrolled       | Brisbane and Eden, Australia| MicroAetholometer AE 51, Aethlabs             | Chevrolet Grand Caravans 2009–2012 | Windows closed and recirculate | 1.7                                                      | 4.0                                                    | Not reported   | Not reported         | 30                         |
| Yang et al. 2015       | Summer, 2103                      | Fixed route        | Hong Kong, China          | MicroAetholometer AE 51, Aethlabs             | Diesel Bus, LPG Bus              | Unknown             | 2.4                                                      | 2.8                                                    | ~ 120          | 1                   |                            |
|                       |                                   |                    |                            |                                               | Diesel Bus, LPG Bus              | Unknown             | 11.6                                                     | 7.6                                                   | ~ 120          | 1                   | 60                         |
|                       |                                   |                    |                            |                                               | Diesel Bus, LPG Bus              | Unknown             | 7.5                                                      | 3.2                                                   | ~ 120          | 4                   | ~ 120                      |
|                       |                                   |                    |                            |                                               | Diesel Bus, LPG Bus              | Unknown             | 2.8                                                      | 3.4                                                   | ~ 120          | 1                   | ~ 120                      |
|                       |                                   |                    |                            |                                               | Diesel Bus, LPG Bus              | Unknown             | 0.4                                                      | 0.3                                                   | ~ 120          | 0.3                 | ~ 120                      |
| Zhang and Zhu 2010     | Spring 2008                       | Fixed route        | Beeville, USA              | AE42 Magee Scientific Aethalometer           | Windows closed, Electric Bus     | Unknown             | 14.2                                                     | 11.3                                                  | 12             | 120                 | Duration of trip          |
|                       |                                   |                    |                            |                                               | Windows closed, Electric Bus     | Unknown             | 7.9                                                      | 3.1                                                   | 12             | 120                 | of trip                   |
|                       |                                   |                    |                            |                                               | Windows closed, Electric Bus     | Unknown             | 12.9                                                     | 4.1                                                   | 15             | 120                 |                            |
| Zuurbier et al. 2010   | 2007–2008                         | Fixed route        | Arnhem, Netherlands        | Model M43D smoke stain reflectometer Converted soot into elemental carbon | Diesel Car, Gasoline Car | Windows closed, A/C on | 14.7                                                     | 4.6                                                   | 15             | 120                 |                            |

*Indicates measurement of elemental carbon and time-integrated studies, the remaining studies measured black carbon using time-resolved methods*
Conclusion

Exposure studies have highlighted that some of the highest exposures to traffic-related pollutants are experienced by people commuting, especially those driving within highly congested urban areas. These exposures are influenced by several factors including cabin air tightness, the use of ventilation and the type of air inlet filters, but there are few studies that address these exposures in detail, and no large studies which assess the effectiveness of these changes. Given the evidence that acute exposures to diesel exhaust is a class 1 carcinogen and have been associated with adverse acute respiratory and cardiovascular effects, it is surprising that the exposures of professional drivers have not received wider attention from a health and safety perspective.

Those people that are required to work in traffic are likely to be disproportionately affected by exposure to air pollution, and whilst this has been acknowledged in occupational health studies, a modern exposure science approach on the time-activity of a professional driver has not been applied. Understanding their activity patterns is essential in providing better information on how to reduce their exposure. Professional drivers represent one of the largest occupational groups, many being self-employed, or employed on temporary contracts. There is an urgent need to better understand exposures in this group and to parameterise the chief determinants of their exposures during the working day, such that low cost, effective mitigation measures can be put in place. The advent of reliable portable sensors for indicators of diesel exhaust exposure alongside use of GPS devices will allow large-scale evaluations of this issue and the cooperation between industry and academia afford the opportunity for the co-design of studies to provide evidence lead solutions to an underappreciated issue. There is therefore a clear need for larger experimental campaigns to fully parameterise the level and chief determinants of in-vehicle exposures in occupational drivers.

Code availability Not applicable.

Funding This research was funded by the Institution of Occupational Safety and Health. IM and BB received further support from the National Institute for Health Research Health Protection Research Unit (NIHR HPRU) in Environmental Exposures and Health at Imperial College in partnership with Public Health England (PHE). The views expressed in this paper are those of the authors and should not be taken to reflect the official position of the funders.
Not applicable.

Not applicable.

The authors declare no conflict of interest.

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