Air Quality, Atmosphere & Health (2021) 14:1681–1695
https://doi.org/10.1007/s11869-021-01048-0

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

Shanon Lim[1] · Lois Holliday[2] · Benjamin Barratt[1,3] · Chris J. Griffiths[2,4] · Ian S. Mudway[1,3,4]

Received: 18 December 2020 / Accepted: 19 May 2021 / Published online: 2 June 2021

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), sub-optimal 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 (Karanasiou et al. 2014). However, few studies

Shanon Lim and Lois Holliday contributed equally to this work.

✉ Shanon Lim
s.lim@imperial.ac.uk

1 MRC Centre for Environment and Health, Environmental Research Group, School of Public Health, Faculty of Medicine, Imperial College London, London, UK

2 Institute of Population Health Sciences, Asthma UK Centre for Applied Research, Barts and the London School of Medicine and Dentistry, Queen Mary University of London, London, UK

3 NIHR Environmental Exposure and Health HPRU, Imperial College London, London, UK

4 MRC and Asthma UK Centre in Allergic Mechanisms of Asthma, King's College London, London, UK

have considered professional drivers who are chronically exposed to the pollutant due to their prolonged work in transport microenvironments (Knibbs 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 (NO_2) 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 (McCreanor et al. 2007; Sinharay et al. 2018). These studies have also shown impacts on lung function, airway inflammation and vascular indices (McCreanor 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 Morawska 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 (Pronk 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 $\mu g/m^3$ 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 $\mu g/m^3$) and Asia (4 to 28 $\mu g/m^3$). 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 $\mu g/m^3$ in Estonia in 2002. The lowest exposures were found in all four studies in the USA (1 to 3 μg/m^3), 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/m^3 (Hachem et al. 2021; Moreno et al. 2019). This is a concern as a study found that a lifetime occupational exposure of 1 μg/m^3 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.

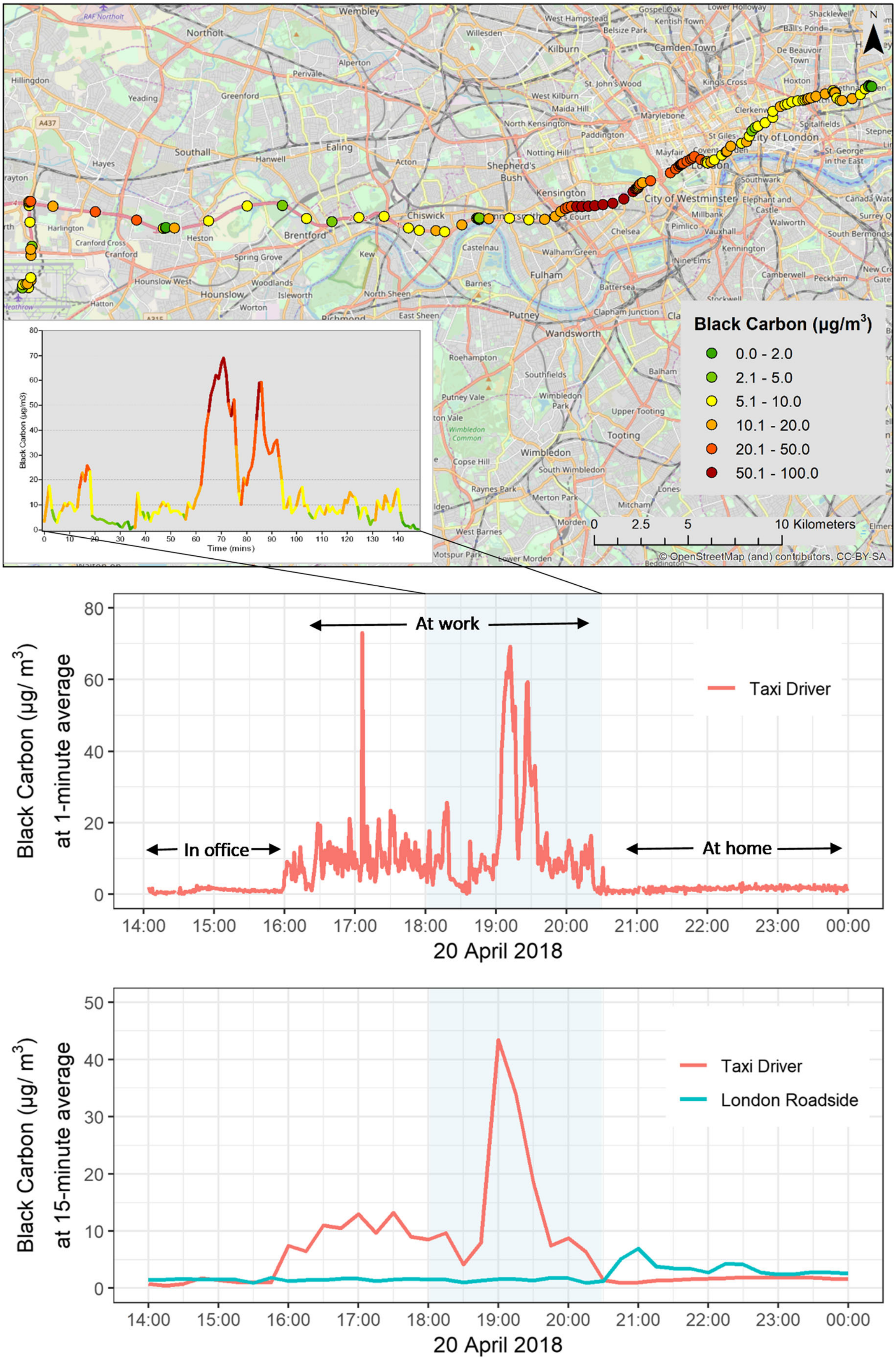
As an illustration of this point, we have included some representative BC exposure data collected from a taxi driver in London, across a single shift (Fig. 1). This highlights several key points: (1) the extremely high peak exposures occurring when travelling through the most congested parts of the city (> 90 μg/m^3); (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.

Blending an exposure science approach to occupational assessment

Whilst some of the occupational studies reviewed employed time-resolved methods, most high-resolution air pollution studies to date have been conducted within the field of exposure science. These type of studies focus on understanding human behaviour and activities to advance our knowledge on the determinants of high exposure to agents (Lioy 2010). Most of these studies assess people's air pollution exposures for a minimum of 24 h to identify events where high exposure events occur throughout their day and quantify contributions of exposures in different microenvironments (Carvalho et al. 2018; Dons et al. 2011; Koehler et al. 2019). This extended duration of monitoring could also be beneficial for occupational studies which typically only measure shift exposures to provide a contrast of occupational exposure compared to other microenvironments in a worker's daily life.

A subset of these exposure science studies have focussed entirely on commuting due to the intensity of pollution exposure experienced in this environment (Karanasiou et al. 2014). Due to the advent of a portable BC monitor (Cheng and Lin

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/m^3. 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



Black Carbon (μg/m3)
0.0 - 2.0
2.1 - 5.0
5.1 - 10.0
10.1 - 20.0
20.1 - 50.0
50.1 - 100.0
0 2.5 5 10 Kilometers
© OpenStreetMap (and) contributors, CC-BY-SA
Black Carbon (μg/m3)
Time (mins)
At work
In office
At home
Taxi Driver
Black Carbon (μg/ m3) at 1-minute average
20 April 2018
Taxi Driver
London Roadside
Black Carbon (μg/ m3) at 15-minute average
20 April 2018

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, teflon 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. 2015[a]	Summer, 2014	Seoul, South Korea	MicroAetholometer AE 51, Aethlabs	Waste removal workers	BC	9.6	3.5	17	8	1 min
Boffetta 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. 2019[a]	Autumn, 2017	Barcelona, Spain	Mini-aethalometer (Magee Scientific)	Taxi drivers	BC	6.5 (M)	–	14	6	10 s
Lewne et al. 2007	2002–2004	Stockholm, Sweden	Pump and quartz filter	Bus and Lorry 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	EC	5.8	4.8	72	8	Duration of shift
Hachem et al. 2020[a]	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. 2021[a]	2019	Paris, France	MicroAetholometer AE 51, Aethlabs	Taxi drivers	BC	2.9 (M)	–	50	~ 10	1 min
Gany et al. 2017[a]	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/m^3 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; Zuurbier 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 $PM_{2.5}$ 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; Zuurbier 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	Ventilation Settings	Mean exposure (μg/m^3) (GM = Geometric Mean, M= Median)	Std Dev (μg/m^3) (GSD = Geometric Std Dev, R= Range)	Number of trips	Time of trip (min)	Time resolution of monitor (s)
Adams et al. 2002	Summer, 1999	Fixed route	London, UK	Pump and Teflon Filters	Car (Summer)	Unknown	21.6 (GM)	2.1 (GSD)	15	16 to 59	Duration of trip
					Bus (Summer)	Unknown	13.6 (GM)	1.9 (GSD)	22		
	Winter, 2000				Car (Winter)	Unknown	27.3 (GM)	2.0 (GSD)	11		
					Bus (Winter)	Unknown	18.6 (GM)	2.3 (GSD)	31		
Adar et al. 2007	Spring 2002	Fixed route	St Louis, US	Magee Scientific Aethalometer	Diesel shuttle bus	Unknown	2.9 (M)	–	4	60	300
Apte et al. 2011	Spring, Summer 2010	Fixed route	New Dehli, India	MicroAetholometer AE 51, Aethlabs	Auto Rickshaw	Unknown	43.0	–	47	180	1
					Car Tata Indica	Windows open	49.0	–	5		
					Car Tata Indica	Windows closed, A/C on	29.0	–	10		
de Nazelle et al. 2012	Summer, 2009	Fixed route	Barcelona, Spain	MicroAetholometer AE 51, Aethlabs	2008 Renault Clio diesel	Window open	19.5	1.8 (GSD)	36	120	1
					Bus	Unknown	7.6	1.5 (GSD)	34		
Dons et al. 2012	Winter, 2010–2011	Uncontrolled	Flanders, Belgium	MicroAetholometer AE 51, Aethlabs	Car driver	Unknown	6.4	–	Not reported	Not report-ed	300
					Car passenger	Unknown	5.6	–			
					Bus Passenger	Unknown	6.6	–			
Fruin et al. 2004	Autumn, 1997	Fixed route	Los Angeles, US	AE16 Aethalometer, Magee	1991 Chevrolet Caprice	Windows closed, A/C on	16	51	16	120	60
			Sacramento, US		Sedan	Windows closed, A/C on	9	11	13		
Ham et al. 2017	2014–2015	Uncontrolled	Sacramento, US	MicroAetholometer AE 51, Aethlabs	Private Vehicle	All	0.5	0.4	101	22	10
						Recirculate	0.3	–	Not reported		
						Outside air	0.4	–	Not reported		
						Windows Open	0.6	–	Not reported		
Jeong and Park 2017	Summer–Winter 2015–2016	Uncontrolled	Seoul, Korea	MicroAetholometer AE 51, Aethlabs	Car, taxi and motorcycle	Unknown	4.2	2.7	Unknown	Unknown	300
					Van and Minibus	Unknown	7.5	9.5			
Lee et al. 2010	Spring, 2007	Fixed route	Lexington, US	MicroAetholometer AE 51, Aethlabs	2005 Ford Taurus	Windows closed	1.5 to 2.5	–	39	60	60
Lei et al. 2017	Autumn, 2015	Fixed route	Shanghai, China	MicroAetholometer AE 51, Aethlabs	Car	Windows open	11.8	9.8	12	40 - 160	30
Li et al. 2015	Summer, 2014	Fixed route	Shanghai, China	MicroAetholometer AE 51, Aethlabs	Taxi	Unknown	8.6	2.6	12	90	1
					Bus	Unknown	7.3	1.6	12		
Morales Betancourt et al. 2017	Dry season 2015	Fixed route	Bogota, Colombia	MicroAetholometer AE 51, Aethlabs	Car/Taxi	Unknown	41.0 (M)	2.9 (GSD)	6	19	30
					BRT-Bus	Unknown	77.5 (M)	2.8 (GSD)	12	15	
Moreno et al. 2015	Autumn 2014	Fixed route	Barcelona, Spain	MicroAetholometer AE 51, Aethlabs	Euro 2 or 3 Bus	Unknown	5.5	3.6	Not reported	80	30

Table 2 (continued)

Author	Year and season of data collection	Type	Location	Equipment	Vehicle type	Ventilation Settings	Mean exposure (µg/m^3) (GM = Geometric Mean, M= Median)	Std Dev (µg/m^3) (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	MicroAethольometer AE 51, Aethlabs	2012 Volvo C50 hybrid	Closed Windows	2.0	0.0 to 19.0 (R)	663	~ 7	60
					Bus	Unknown	2.7	0.2 to 37.2 (R)	1251	~ 11	60
Okokon et al. 2017	Spring, 2011	Fixed route	Helsinki, Finland	MicroAethalometer AE 51, Aethlabs	Ford Focus Wagon (2008-2010)	Open Windows	7.8	4.3	6	20	60
					Ford Focus Wagon (2008–010)	Closed Windows	2.8	2.3	6	20	
					Bus	Unknown	4.6	4.4	6	23	
			Rotterdam, Netherlands		Ford Focus Wagon (2008–2010)	Open Windows	6.4	3.3	6	23	
					Ford Focus Wagon (2008–2010)	Closed Windows	6.3	3.4	6	23	
					Bus	Unknown	4.3	2.6	6	27	
			Thessaloniki, Greece		Ford Focus Wagon (2008–2010)	Open Windows	10.9	9.9	6	21	
					Ford Focus Wagon (2008–2010)	Closed Windows	4.7	3.4	6	21	
					Bus	Unknown	8.5	5.1	6	32	
Pant et al. 2017	2014–2016	Fixed route	New Dehli, India	MicroAethalometer AE 51, Aethlabs	Bus	Unknown	17.1	10.6	Unknown	Unknown	60
Patton et al. 2016	2007–2014	Fixed route	New Jersey Turnpike, US	MicroAethalometer AE 51, Aethlabs	Varied Cars	Windows closed, outside air	4.0 (M)	-	190	Unknown	1
Rivas et al. 2017	Spring, 2016	Fixed route	London, UK	MicroAethalometer AE 51, Aethlabs	Petrol Peugeot 208 Active 1.2	Windows closed and recirculate	4.4 (GM)	2.5 (GSD)	90	49 to 66	10
					Bus	Unknown	5.4 (GM)	2.3 (GSD)	47		
Sarnat et al. 2014	2009 - 2011	Fixed route	Atlanta, US	MicroAethalometer AE 51, Aethlabs	Varied cars	Mixed	6.6	3.3	78	120	Not reported
Targino et al. 2018	Autumn 2014	Fixed route	Londrina, Brazil	MicroAethalometer AE 51, Aethlabs	Unspecified Bus	Mixed	9.6	12.2	8	120	Not reported
Tan et al. 2017	Dry season 2013	Fixed route	Singapore	MicroAethalometer AE 51, Aethlabs	Taxi	Windows closed and recirculate	2.9 (GM)	3.9 (GSD)	23	8	1
					Bus	Unknown	3.2 (GM)	3.3 (GSD)	23	7	
Vouitsis et al. 2014	Spring 2011	Fixed route	Thessaloniki, Greece	MicroAethalometer AE 51, Aethlabs	2008-2010 Ford Focus	Windows open	9.0	4.8	12	~ 24	1

Table 2 (continued)

Author	Year and season of data collection	Type	Location	Equipment	Vehicle type	Ventilation Settings	Mean exposure (μg/m^3) (GM = Geometric Mean, M= Median)	Std Dev (μg/m^3) (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	
					Bus	Unknown	7.4	3.1	12	~ 28	
Weichenthal et al. 2015	Summer and Winter, 2010	Fixed route	Toronto, Canada	MicroAetholometer AE 51, Aethlabs	Chevrolet Grand Caravans 2009–2012	Windows Closed	1.4 (M)	0.3 to 6.9 (R)	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	2008 Petrol Volkswagen Jetta	Windows closed and recirculate	1.7	4.0	Not reported	Not report-ed	30
					2008 Petrol Volkswagen Jetta	Windows open	4.4	7.3			
					Bus	Unknown	2.4	2.8			
Yang et al. 2015	Summer. 2103	Fixed route	Hong Kong, China	MicroAetholometer AE 51, Aethlabs	Diesel Bus	Unknown	11.6	7.6	60	~ 120	1
					LPG Bus	Unknown	7.5	3.2	17	~ 120	
					1990 Bus	Windows open	2.8	3.4	4	~ 120	60
Zhang and Zhu 2010	Spring 2008	Fixed route	Beeville, USA	AE42 Magee Scientific Aethalometer	1990 Bus	Windows closed	2.3	0.8	4	~ 120	
					2006 Bus	Windows open	2.9	2.3	4	~ 120	
					2006 Bus	Windows closed	0.4	0.3	1	~ 120	
Zuurbier et al. 2010	2007–2008	Fixed route	Arnhem, Netherlands	Model M43D smoke stain reflectometer Converted soot into elemental carbon	Diesel Bus	Windows closed	14.2	11.3	12	120	Duration of trip
					Electric Bus	Windows closed	7.9	3.1	12	120	
					Diesel Car	Windows closed, A/C on	12.9	4.1	15	120	
					Gasoline Car	Windows closed, A/C on	14.7	4.6	15	120	

[a] Indicates measurement of elemental carbon and time-integrated studies, the remaining studies measured black carbon using time-resolved methods

Fig. 2 Key determinants of the concentration of traffic derived pollutants within vehicles

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.

Data availability Not applicable.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no conflict of interest.

References

Adams H, Nieuwenhuijsen MJ, Colvile RN, Older MJ, Kendall M (2002) Assessment of road users' elemental carbon personal exposure levels, London, UK. *Atmos Environ 36*(34):5335–5342. https://doi.org/10.1016/S1352-2310(02)00637-4

Adar SD, Gold DR, Coull BA, Schwartz J, Stone PH, Suh H (2007) Focused exposures to airborne traffic particles and heart rate variability in the elderly. *Epidemiology 18*(1):95–103. https://doi.org/10.1097/01.ede.0000249409.81050.46

Alexeeff SE, Roy A, Shan J, Liu X, Messier K, Apte JS, Portier C, Sidney S, Van Den Eeden SK (2018) High-resolution mapping of traffic related air pollution with Google street view cars and incidence of cardiovascular events within neighborhoods in Oakland, CA. *Environ Health 17*(1):38. https://doi.org/10.1186/s12940-018-0382-1

Alvarez-Pedrerol M, Rivas I, López-Vicente M, Suades-González E, Donaire-Gonzalez D, Cirach M, de Castro M, Esnaola M, Basagaña X, Dadvand P, Nieuwenhuijsen M, Sunyer J (2017) Impact of commuting exposure to traffic-related air pollution on cognitive development in children walking to school. *Environmental Pollution*, *231, Part 1*:837–844. https://doi.org/10.1016/j.envpol.2017.08.075

Anenberg SC, Miller J, Minjares R, Du L, Henze DK, Lacey F, Malley CS, Emberson L, Franco V, Klimont Z, Heyes C (2017) Impacts and mitigation of excess diesel-related NOx emissions in 11 major vehicle markets. *Nature 545*(7655):467–471. https://doi.org/10.1038/nature22086

Apte JS, Kirchstetter TW, Reich AH, Deshpande SJ, Kaushik G, Chel A, Marshall JD, Nazaroff WW (2011) Concentrations of fine, ultrafine, and black carbon particles in auto-rickshaws in New Delhi, India. *Atmos Environ 45*(26):4470–4480. https://doi.org/10.1016/j.atmosenv.2011.05.028

Atkinson RW, Fuller GW, Anderson HR, Harrison RM, Armstrong B (2010) Urban ambient particle metrics and health: a time-series analysis. *Epidemiology (Cambridge, Mass) 21*(4):501–511. PubMed. https://doi.org/10.1097/ede.0b013e3181debc88

Atkinson RW, Analitis A, Samoli E, Fuller GW, Green DC, Mudway IS, Anderson HR, Kelly FJ (2016) Short-term exposure to traffic-related air pollution and daily mortality in London, UK. *Journal of Exposure Science & Environmental Epidemiology 26*(2):125–132. PubMed. https://doi.org/10.1038/jes.2015.65

Baccarelli AA, Zheng Y, Zhang X, Chang D, Liu L, Wolf KR, Zhang Z, McCracken JP, Díaz A, Bertazzi PA, Schwartz J, Wang S, Kang C-M, Koutrakis P, Hou L (2014) Air pollution exposure and lung function in highly exposed subjects in Beijing, China: a repeated-measure study. *Particle and Fibre Toxicology 11*(1):51. https://doi.org/10.1186/s12989-014-0051-7

Barath S, Mills NL, Lundbäck M, Törnqvist H, Lucking AJ, Langrish JP, Söderberg S, Boman C, Westerholm R, Löndahl J, Donaldson K, Mudway IS, Sandström T, Newby DE, Blomberg A (2010) Impaired vascular function after exposure to diesel exhaust generated at urban transient running conditions. *Particle and Fibre Toxicology 7*(1):19. https://doi.org/10.1186/1743-8977-7-19

Bell ML, Ebisu K, Leaderer BP, Gent JF, Lee HJ, Koutrakis P, Wang Y, Dominici F, Peng RD (2014) Associations of $PM_{2.5}$ constituents and sources with hospital admissions: analysis of four counties in Connecticut and Massachusetts (USA) for persons ≥ 65 years of age. *Environ Health Perspect 122*(2):138–144. https://doi.org/10.1289/ehp.1306656

Boffetta P, Cherrie J, Hughson G, & Pitard A (2002). *Cancer risk from diesel emissions exposure in Central and Eastern Europe: A feasibility study.* (HEI Special Report. Research Directions to Improve Estimates of Human Exposure and Risk from Diesel Exhaust. A Special Report of the Institute's Diesel Epidemiology Working Group., pp. 57–78). Health Effects Institute; Boston, MA

Bond TC, Doherty SJ, Fahey DW, Forster PM, Berntsen T, DeAngelo BJ, Flanner MG, Ghan S, Kärcher B, Koch D, Kinne S, Kondo Y, Quinn PK, Sarofim MC, Schultz MG, Schulz M, Venkataraman C, Zhang H, Zhang S, Bellouin N, Guttikunda SK, Hopke PK, Jacobson MZ, Kaiser JW, Klimont Z, Lohmann U, Schwarz JP, Shindell D, Storelvmo T, Warren SG, Zender CS (2013) Bounding the role of black carbon in the climate system: A scientific assessment. *J Geophys Res-Atmos 118*(11):5380–5552. https://doi.org/10.1002/jgrd.50171

Bos B, Lim S, Hedges M, Molden N, Boyle S, Mudway I, Barratt B (2021) Taxi drivers' exposure to black carbon and nitrogen dioxide in electric and diesel vehicles: a case study in London. *Environ Res 195*:110736. https://doi.org/10.1016/j.envres.2021.110736

Brauer M, Brumm J, Vedal S, Petkau AJ (2002) Exposure misclassification and threshold concentrations in time series analyses of air pollution health effects. *Risk Anal 22*(6):1183–1193. https://doi.org/10.1111/1539-6924.00282

Briggs NL, Long CM (2016) Critical review of black carbon and elemental carbon source apportionment in Europe and the United States. *Atmos Environ 144*:409–427. https://doi.org/10.1016/j.atmosenv.2016.09.002

Brokamp C, Brandt EB, Ryan PH (2019) Assessing exposure to outdoor air pollution for epidemiological studies: model-based and personal sampling strategies. *J Allergy Clin Immunol 143*(6):2002–2006. https://doi.org/10.1016/j.jaci.2019.04.019

Brucker N, Nascimento SN, Bernardini L, Charão MF, Garcia SC (2020) Biomarkers of exposure, effect, and susceptibility in occupational exposure to traffic-related air pollution: a review. *J Appl Toxicol*, jat.3940 40:722–736. https://doi.org/10.1002/jat.3940

Brunekreef B, Stewart AW, Andersen R, Lai CKW, Strachan DP, Pearce N (2009) Self-reported truck traffic on the street of residence and symptoms of asthma and allergic disease: a global relationship in ISAAC Phase 3. *Environ Health Perspect 117*(11):1791–1798. https://doi.org/10.1289/ehp.0800467

Cames M, Helmers E (2013) Critical evaluation of the European diesel car boom—Global comparison, environmental effects and various national strategies. *Environ Sci Eur 25*(15)

Carey IM, Anderson HR, Atkinson RW, Beevers S, Cook DG, Dajnak D, Gulliver J, Kelly FJ (2016) Traffic pollution and the incidence of cardiorespiratory outcomes in an adult cohort in London. *Occup Environ Med 73*(12):849–856. https://doi.org/10.1136/oemed-2015-103531

Carvalho AM, Krecl P, Targino AC (2018) Variations in individuals' exposure to black carbon particles during their daily activities: a screening study in Brazil. *Environ Sci Pollut Res 25*(19):18412–18423. https://doi.org/10.1007/s11356-018-2045-8

Chambers M, & Schmitt R (2015). *Diesel-powered passenger cars and light trucks* (p. 4). U.S Department of Transportation

Cheng Y-H, Lin M-H (2013) Real-time performance of the microAeth® AE51 and the effects of aerosol loading on its measurement results at a traffic site. *Aerosol Air Qual Res 13*(6):1853–1863. https://doi.org/10.4209/aaqr.2012.12.0371

Davis ME, Smith TJ, Laden F, Hart JE, Blicharz AP, Reaser P, Garshick E (2007) Driver exposure to combustion particles in the U.S. Trucking industry. *J Occup Environ Hyg 4*(11):848–854. PubMed. https://doi.org/10.1080/15459620701643347

de Hoogh K, Chen J, Gulliver J, Hoffmann B, Hertel O, Ketzel M, Bauwelinck M, van Donkelaar A, Hvidtfeldt UA, Katsouyanni K, Klompmaker J, Martin RV, Samoli E, Schwartz PE, Stafoggia M, Bellander T, Strak M, Wolf K, Vienneau D, Brunekreef B, Hoek G (2018) Spatial PM2.5, NO2, O3 and BC models for Western Europe—evaluation of spatiotemporal stability. *Environ Int 120*: 81–92. https://doi.org/10.1016/j.envint.2018.07.036

de Nazelle A, Fruin S, Westerdahl D, Martinez D, Ripoll A, Kubesch N, Nieuwenhuijsen M (2012) A travel mode comparison of commuters' exposures to air pollutants in Barcelona. *Atmos Environ 59*:151–159. https://doi.org/10.1016/j.atmosenv.2012.05.013

Dons E, Int Panis L, Van Poppel M, Theunis J, Willems H, Torfs R, Wets G (2011) Impact of time–activity patterns on personal exposure to black carbon. *Atmos Environ 45*(21):3594–3602. https://doi.org/10.1016/j.atmosenv.2011.03.064

Dons E, Int Panis L, Van Poppel M, Theunis J, Wets G (2012) Personal exposure to Black Carbon in transport microenvironments. *Atmos Environ 55*:392–398. https://doi.org/10.1016/j.atmosenv.2012.03.020

Dons E, Temmerman P, Van Poppel M, Bellemans T, Wets G, Int Panis L (2013) Street characteristics and traffic factors determining road users' exposure to black carbon. *Sci Total Environ 447*:72–79. https://doi.org/10.1016/j.scitotenv.2012.12.076

Du X, Fu L, Ge W, Zhang S, Wang H (2011) Exposure of taxi drivers and office workers to traffic-related pollutants in Beijing: a note. *Transp Res Part D: Transp Environ 16*(1):78–81. https://doi.org/10.1016/j.trd.2010.08.002

European Environment Agency (2013) *Status of black carbon monitoring in ambient air in Europe*. Publications Office. http://dx.publications.europa.eu/10.2800/10150

European Environment Agency. (2018). *Dieselisation (share of diesel cars in the total passenger car fleet)* [Data Visualization]. European Environment Agency. https://www.eea.europa.eu/data-and-maps/daviz/dieselisation-of-diesel-cars-in-4#tab-chart_1

Fang SC, Cassidy A, Christiani DC (2010) A systematic review of occupational exposure to particulate matter and cardiovascular disease. *Int J Environ Res Public Health 7*(4):1773–1806. PubMed. https://doi.org/10.3390/ijerph7041773

Fiebig M, Wiartalla A, Holderbaum B, Kiesow S (2014) Particulate emissions from diesel engines: Correlation between engine technology and emissions. *Journal of Occupational Medicine and Toxicology 9*(1):6. https://doi.org/10.1186/1745-6673-9-6

Fruin S, Winer AM, Rodes CE (2004) Black carbon concentrations in California vehicles and estimation of in-vehicle diesel exhaust particulate matter exposures. *Atmos Environ 38*(25):4123–4133. https://doi.org/10.1016/j.atmosenv.2004.04.026

Gany F, Bari S, Prasad L, Leng J, Lee T, Thurston GD, Gordon T, Acharya S, Zelikoff JT (2017) Perception and reality of particulate matter exposure in New York City taxi drivers. *Journal of Exposure Science & Environmental Epidemiology 27*(2):221–226. https://doi.org/10.1038/jes.2016.23

Garshick E, Laden F, Hart JE, Davis ME, Eisen EA, Smith TJ (2012) Lung cancer and elemental carbon exposure in trucking industry workers. *Environ Health Perspect 120*(9):1301–1306. https://doi.org/10.1289/ehp.1204989

Gehring U, Wijga AH, Hoek G, Bellander T, Berdel D, Brüske I, Fuertes E, Gruzieva O, Heinrich J, Hoffmann B, de Jongste JC, Klümper C, Koppelman GH, Korek M, Krämer U, Maier D, Melén E, Pershagen G, Postma DS, Standl M, von Berg A, Anto JM, Bousquet J, Keil T, Smit HA, Brunekreef B (2015) Exposure to air pollution and development of asthma and rhinoconjunctivitis throughout childhood and adolescence: a population-based birth cohort study. *Lancet Respir Med 3*(12):933–942. https://doi.org/10.1016/S2213-2600(15)00426-9

Good N, Molter A, Ackerson C, Bachand A, Carpenter T, Clark ML, Fedak KM, Kayne A, Koehler K, Moore B, L'Orange C, Quinn C, Ugave V, Stuart AL, Peel JL, Volckens J (2016) The fort Collins commuter study: impact of route type and transport mode on personal exposure to multiple air pollutants. *Journal of Exposure Science and Environmental Epidemiology 26*(4):397–404. https://doi.org/10.1038/jes.2015.68

Hachem M, Bensefa-Colas L, Lahoud N, Akel M, Momas I, Saleh N (2020) Cross-sectional study of in-vehicle exposure to ultrafine particles and black carbon inside Lebanese taxicabs. *Indoor Air* 12703: 1308–1316. https://doi.org/10.1111/ina.12703

Hachem M, Saleh N, Bensefa-Colas L, Momas I (2021) Determinants of ultrafine particles, black carbon, nitrogen dioxide, and carbon monoxide concentrations inside vehicles in the Paris area: PUF-TAXI study. *Indoor Air 31*(3):848–859. https://doi.org/10.1111/ina.12779

Ham W, Vijayan A, Schulte N, Herner JD (2017) Commuter exposure to PM2.5, BC, and UFP in six common transport microenvironments in Sacramento, California. *Atmos Environ 167*:335–345. https://doi.org/10.1016/j.atmosenv.2017.08.024

Harik G, El-Fadel M, Shihadeh A, Alameddine I, Hatzopoulou M (2017) Is in-cabin exposure to carbon monoxide and fine particulate matter amplified by the vehicle's self-pollution potential? Quantifying the rate of exhaust intrusion. *Transp Res Part D: Transp Environ 54*: 225–238. https://doi.org/10.1016/j.trd.2017.05.009

Hart JE, Spiegelman D, Beelen R, Hoek G, Brunekreef B, Schouten LJ, van den Brandt P (2015) Long-term ambient residential traffic-related exposures and measurement error-adjusted risk of incident lung cancer in the netherlands cohort study on diet and cancer. *Environ Health Perspect 123*(9):860–866. https://doi.org/10.1289/ehp.1408762

Health Effects Institute. (2010). *Traffic-related air pollution: a critical review of the literature on emissions, exposure, and health effects* (HEI Special Report 17, p. 386)

Hessey I, Butterfield D, Beccaceci S, Quincey P, Sweeney B, Lilley A, Bradshaw C, Fuller G, Green D, Font A (2017) *2016 annual report for the uk black carbon network*:81

Hoek G, Brunekreef B, Goldbohm S, Fischer P, van den Brandt PA (2002) Association between mortality and indicators of traffic-related air pollution in the Netherlands: a cohort study. *Lancet 360*(9341):1203–1209. https://doi.org/10.1016/S0140-6736(02)11280-3

International Agency for Research on Cancer. (2012). *Diesel engine exhaust carcinogenic*. https://www.iarc.fr/wp-content/uploads/2018/07/pr213_E.pdf

Janssen NA, Brunekreef B, van Vliet P, Aarts F, Meliefste K, Harssema H, Fischer P (2003) The relationship between air pollution from heavy traffic and allergic sensitization, bronchial hyperresponsiveness, and respiratory symptoms in Dutch schoolchildren. *Environ Health Perspect 111*(12):1512–1518. PubMed. https://doi.org/10.1289/ehp.6243

Janssen NA, Hoek G, Simic-Lawson M, Fischer P, van Bree L, ten Brink H, Keuken M, Atkinson RW, Anderson HR, Brunekreef B, Cassee FR (2011) Black carbon as an additional indicator of the adverse health effects of airborne particles compared with PM10 and PM2.5. *Environ Health Perspect 119*(12):1691–1699. https://doi.org/10.1289/ehp.1003369

Jeong H, Park D (2017) Characteristics of elementary school children's daily exposure to black carbon (BC) in Korea. *Atmos Environ 154*: 179–188. https://doi.org/10.1016/j.atmosenv.2017.01.045

Jinsart W, Kaewmanee C, Inoue M, Hara K, Hasegawa S, Karita K, Tamura K, Yano E (2012) Driver exposure to particulate matter in Bangkok. *J Air Waste Manage Assoc 62*(1):64–71. https://doi.org/10.1080/10473289.2011.622854

Jones RR, Hoek G, Fisher JA, Hasheminassab S, Wang D, Ward MH, Sioutas C, Vermeulen R, Silverman DT (2020) Land use regression models for ultrafine particles, fine particles, and black carbon in Southern California. *Sci Total Environ 699*:134234. https://doi.org/10.1016/j.scitotenv.2019.134234

Karanasiou A, Viana M, Querol X, Moreno T, de Leeuw F (2014) Assessment of personal exposure to particulate air pollution during commuting in European cities—recommendations and policy implications. *Sci Total Environ 490*:785–797. https://doi.org/10.1016/j.scitotenv.2014.05.036

Kaur S, Nieuwenhuijsen MJ, Colvile RN (2007) Fine particulate matter and carbon monoxide exposure concentrations in urban street transport microenvironments. *Atmos Environ 41*(23):4781–4810. https://doi.org/10.1016/j.atmosenv.2007.02.002

Knibbs LD, Morawska L (2012) Traffic-related fine and ultrafine particle exposures of professional drivers and illness: an opportunity to better link exposure science and epidemiology to address an occupational hazard? *Environ Int 49*:110–114. https://doi.org/10.1016/j.envint.2012.08.013

Koehler K, Good N, Wilson A, Mölter A, Moore BF, Carpenter T, Peel JL, Volckens J (2019) The Fort Collins commuter study: variability in personal exposure to air pollutants by microenvironment. *Indoor Air 29*(2):231–241. https://doi.org/10.1111/ina.12533

Lawin H, Ayi Fanou L, Hinson A, Stolbrink M, Houngbegnon P, Kedote N, Fayomi B, Kagima J, Katoto P, Ouendo E, Mortimer K (2018) Health risks associated with occupational exposure to ambient air pollution in commercial drivers: a systematic review. *Int J Environ Res Public Health 15*(9):2039. https://doi.org/10.3390/ijerph15092039

Lee BK, Smith TJ, Garshick E, Natkin J, Reaser P, Lane K, Lee HK (2005) Exposure of trucking company workers to particulate matter during the winter and summer. In: Yang X, Zhao B, Zhao R (eds) *Indoor Air 2005: Proceedings of the 10th International Conference on Indoor Air Quality and Climate*, vol *1-5*, pp 2640–2644

Lee K, Sohn H, Putti K (2010) In-vehicle exposures to particulate matter and black carbon. *J Air Waste Manage Assoc 60*(2):130–136. https://doi.org/10.3155/1047-3289.60.2.130

Lee K-H, Jung H-J, Park D-U, Ryu S-H, Kim B, Ha K-C, Kim S, Yi G, Yoon C (2015) Occupational exposure to diesel particulate matter in municipal household waste workers. *PLoS One 10*(8):e0135229. https://doi.org/10.1371/journal.pone.0135229

Lei X, Bian J, Xiu G, Hu X, Gu X, Bian Q (2017) The mobile monitoring of black carbon and its association with roadside data in the Chinese megacity of Shanghai. *Environ Sci Pollut Res 24*(8):7482–7489. https://doi.org/10.1007/s11356-017-8454-2

Lewne M, Plato N, Gustavsson P (2007) Exposure to particles, elemental carbon and nitrogen dioxide in workers exposed to motor exhaust. *Ann Occup Hyg 51*(8):693–701. https://doi.org/10.1093/annhyg/mem046

Li B, Lei XN, Xiu GL, Gao CY, Gao S, Qian NS (2015) Personal exposure to black carbon during commuting in peak and off-peak hours in Shanghai. *Sci Total Environ 524–525*:237–245. https://doi.org/10.1016/j.scitotenv.2015.03.088

Lim S, Salmond JA, Dirks KN (2015) Influence of differing microenvironments on personal carbon monoxide exposure in Auckland, New Zealand. *The Open Atmospheric Science Journal 9*(1):1–8. https://doi.org/10.2174/1874282301509010001

Lioy PJ (2010) Exposure science: a view of the past and milestones for the future. *Environ Health Perspect 118*(8):1081–1090. https://doi.org/10.1289/ehp.0901634

McCreanor J, Cullinan P, Nieuwenhuijsen MJ, Stewart-Evans J, Malliarou E, Jarup L, Harrington R, Svartengren M, Han I-K, Ohman-Strickland P, Chung KF, Zhang J (2007) Respiratory effects of exposure to diesel traffic in persons with asthma. *N Engl J Med 357*(23):2348–2358. https://doi.org/10.1056/NEJMoa071535

Merritt A-S, Georgellis A, Andersson N, Bero Bedada G, Bellander T, Johansson C (2019) Personal exposure to black carbon in Stockholm, using different intra-urban transport modes. *Sci Total Environ 674*:279–287. https://doi.org/10.1016/j.scitotenv.2019.04.100

Miller-Schulze JP, Paulsen M, Toriba A, Tang N, Hayakawa K, Tamura K, Dong L, Zhang X, Simpson CD (2010) Exposures to particulate air pollution and nitro-polycyclic aromatic hydrocarbons among taxi drivers in Shenyang, China. *Environ Sci Technol 44*(1):216–221. https://doi.org/10.1021/es802392u

Mills NL, Törnqvist H, Gonzalez MC, Vink E, Robinson SD, Söderberg S, Boon NA, Donaldson K, Sandström T, Blomberg A, Newby DE (2007) Ischemic and thrombotic effects of dilute diesel-exhaust inhalation in men with coronary heart disease. *N Engl J Med 357*(11):1075–1082. https://doi.org/10.1056/NEJMoa066314

Monks, P. S., ApSimon, H., Carruthers, D., Carslaw, D. C., Derwent, D., Harrison, R. M., Laxen, D., & Stedman, J. (2012). *Fine particulate matter (PM2.5) in the United Kingdom*. Department for Environment, Food and Rural Affairs; https://uk-air.defra.gov.uk/assets/documents/reports/cat11/1212141150_AQEG_Fine_Particulate_Matter_in_the_UK.pdf

Morales Betancourt R, Galvis B, Balachandran S, Ramos-Bonilla JP, Sarmiento OL, Gallo-Murcia SM, Contreras Y (2017) Exposure to fine particulate, black carbon, and particle number concentration in transportation microenvironments. *Atmos Environ 157*:135–145. https://doi.org/10.1016/j.atmosenv.2017.03.006

Moreno T, Reche C, Rivas I, Cruz Minguillón M, Martins V, Vargas C, Buonanno G, Parga J, Pandolfi M, Brines M, Ealo M, Sofia Fonseca A, Amato F, Sosa G, Capdevila M, de Miguel E, Querol X, Gibbons W (2015) Urban air quality comparison for bus, tram, subway and pedestrian commutes in Barcelona. *Environ Res 142*:495–510. https://doi.org/10.1016/j.envres.2015.07.022

Moreno T, Pacitto A, Fernández A, Amato F, Marco E, Grimalt JO, Buonanno G, Querol X (2019) Vehicle interior air quality conditions when travelling by taxi. *Environ Res 172*:529–542. https://doi.org/10.1016/j.envres.2019.02.042

Mudway IS, Dundas I, Wood HE, Marlin N, Jamaludin JB, Bremner SA, Cross L, Grieve A, Nanzer A, Barratt BM, Beevers S, Dajnak D, Fuller GW, Font A, Colligan G, Sheikh A, Walton R, Grigg J, Kelly FJ, Lee TH, Griffiths CJ (2019) Impact of London's low emission zone on air quality and children's respiratory health: a sequential annual cross-sectional study. *Lancet Public Health 4*(1):e28–e40. https://doi.org/10.1016/S2468-2667(18)30202-0

National Institute for Occupational Safety and Health (1994) Diesel particulate matter (as elemental carbon), Method 5040 by M. Eileen Birch. In: Schlecht PC, O'Connor PF (eds) *NIOSH Manual of Analytical Methods* (4th ed.). DHHS (NIOSH) Pub, pp 94–113

Ngo NS, Gatari M, Yan B, Chillrud SN, Bouhamam K, Kinney PL (2015) Occupational exposure to roadway emissions and inside informal settlements in sub-Saharan Africa: a pilot study in Nairobi, Kenya. *Atmos Environ 111*:179–184. https://doi.org/10.1016/j.atmosenv.2015.04.008

Okokon EO, Yli-Tuomi T, Turunen AW, Taimisto P, Pennanen A, Vouitsis I, Samaras Z, Voogt M, Keuken M, Lanki T (2017) Particulates and noise exposure during bicycle, bus and car commuting: a study in three European cities. *Environ Res 154*:181–189. https://doi.org/10.1016/j.envres.2016.12.012

Pant P, Habib G, Marshall JD, Peltier RE (2017) PM2.5 exposure in highly polluted cities: a case study from New Delhi, India. *Environ Res 156*:167–174. https://doi.org/10.1016/j.envres.2017.03.024

Patton AP, Laumbach R, Ohman-Strickland P, Black K, Alimokhtari S, Lioy P, Kipen HM (2016) Scripted drives: a robust protocol for generating exposures to traffic-related air pollution. *Atmos Environ 143*:290–299. https://doi.org/10.1016/j.atmosenv.2016.08.038

Petzold A, Ogren JA, Fiebig M, Laj P, Li S-M, Baltensperger U, Holzer-Popp T, Kinne S, Pappalardo G, Sugimoto N, Wehrli C, Wiedensohler A, Zhang X-Y (2013) Recommendations for reporting 'black carbon' measurements. *Atmos Chem Phys 13*(16): 8365–8379. https://doi.org/10.5194/acp-13-8365-2013

Pfeffer PE, Donaldson GC, Mackay AJ, Wedzicha JA (2018) Increased chronic obstructive pulmonary disease exacerbations of likely viral etiology follow elevated ambient nitrogen oxides. *Am J Respir Crit Care Med 199*(5):581–591. https://doi.org/10.1164/rccm.201712-2506OC

Pronk A, Coble J, Stewart PA (2009) Occupational exposure to diesel engine exhaust: a literature review. *Journal of Exposure Science & Environmental Epidemiology 19*(5):443–457. PubMed. https://doi.org/10.1038/jes.2009.21

Ramachandran G, Paulsen D, Watts W, Kittelson D (2005) Mass, surface area and number metrics in diesel occupational exposure assessment. *J Environ Monit 7*(7):728–735. https://doi.org/10.1039/B503854E

Rivas I, Kumar P, Hagen-Zanker A (2017) Exposure to air pollutants during commuting in London: are there inequalities among different socio-economic groups? *Environ Int 101*:143–157. https://doi.org/10.1016/j.envint.2017.01.019

Rushton L, Hutchings SJ, Fortunato L, Young C, Evans GS, Brown T, Bevan R, Slack R, Holmes P, Bagga S, Cherrie JW, Van Tongeren M (2012) Occupational cancer burden in Great Britain. *British Journal of Cancer*, *107 Suppl 1*(Suppl 1):S3–S7. PubMed. https://doi.org/10.1038/bjc.2012.112

Salako GO, Hopke PK, Cohen DD, Begum BA, Biswas SK, Pandit GG, Lodoysamba S, Wimolwattanapun W, Bunprapob S, Chung Y-S, Rahman SA, Hamzah MS, Davy P, Markwitz A, Shagjjamba D (2012) Exploring the Variation between EC and BC in a Variety of Locations. *Aerosol Air Qual Res 12*(1):1–7. https://doi.org/10.4209/aaqr.2011.09.0150

Salvi S, Blomberg A, Rudell B, Kelly F, Sandström T, Holgate S, Frew A (1999) Acute inflammatory responses in the airways and peripheral blood after short-term exposure to diesel exhaust in healthy human volunteers. *Am J Respir Crit Care Med 159*(3):702–709. PubMed. https://doi.org/10.1164/ajrccm.159.3.9709083

Samoli E, Atkinson RW, Analitis A, Fuller GW, Green DC, Mudway I, Anderson HR, Kelly FJ (2016) Associations of short-term exposure to traffic-related air pollution with cardiovascular and respiratory hospital admissions in London, UK. *Occup Environ Med 73*(5): 300–307. https://doi.org/10.1136/oemed-2015-103136

Sarnat JA, Golan R, Greenwald R, Raysoni AU, Kewada P, Winquist A, Sarnat SE, Dana Flanders W, Mirabelli MC, Zora JE, Bergin MH, Yip F (2014) Exposure to traffic pollution, acute inflammation and autonomic response in a panel of car commuters. *Environ Res 133*: 66–76. https://doi.org/10.1016/j.envres.2014.05.004

Silverman DT, Samanic CM, Lubin JH, Blair AE, Stewart PA, Vermeulen R, Coble JB, Rothman N, Schleiff PL, Travis WD, Ziegler RG, Wacholder S, Attfield MD (2012) The diesel exhaust in miners study: a nested case–control study of lung cancer and diesel exhaust. *JNCI: Journal of the National Cancer Institute 104*(11):855–868. https://doi.org/10.1093/jnci/djs034

Sinharay R, Gong J, Barratt B, Ohman-Strickland P, Ernst S, Kelly FJ, Zhang J, Collins P, Cullinan P, Chung KF (2018) Respiratory and cardiovascular responses to walking down a traffic-polluted road compared with walking in a traffic-free area in participants aged 60 years and older with chronic lung or heart disease and age-matched healthy controls: a randomised, crossover study. *Lancet 391*(10118):339–349. https://doi.org/10.1016/S0140-6736(17)32643-0

Smith RB, Fecht D, Gulliver J, Beevers SD, Dajnak D, Blangiardo M, Ghosh RE, Hansell AL, Kelly FJ, Anderson HR, Toledano MB (2017) Impact of London's road traffic air and noise pollution on birth weight: retrospective population based cohort study. *BMJ 359*: j5299. https://doi.org/10.1136/bmj.j5299

Sun Y, Bochmann F, Nold A, Mattenklott M (2014) Diesel exhaust exposure and the risk of lung Cancer—a review of the epidemiological evidence. *Int J Environ Res Public Health 11*(2):1312–1340. https://doi.org/10.3390/ijerph110201312

Tan SH, Roth M, Velasco E (2017) Particle exposure and inhaled dose during commuting in Singapore. *Atmos Environ 170*:245–258. https://doi.org/10.1016/j.atmosenv.2017.09.056

Targino AC, Rodrigues MVC, Krecl P, Cipoli YA, Ribeiro JPM (2018) Commuter exposure to black carbon particles on diesel buses, on bicycles and on foot: a case study in a Brazilian city. *Environ Sci Pollut Res 25*(2):1132–1146. https://doi.org/10.1007/s11356-017-0517-x

Tartakovsky L, Baibikov V, Czerwinski J, Gutman M, Kasper M, Popescu D, Veinblat M, Zvirin Y (2013) In-vehicle particle air pollution and its mitigation. *Atmos Environ 64*:320–328. https://doi.org/10.1016/j.atmosenv.2012.10.003

U.S. Environment Protection Agency. (2012). *Report to congress on black carbon* (p. 351). https://19january2017snapshot.epa.gov/www3/airquality/blackcarbon/2012report/fullreport.pdf

Vardoulakis S, Fisher B, Pericleous K, Gonzalez-Flesca N (2003) Modelling air quality in street canyons: A review. *Atmos Environ 37*:155–182

Vermeulen R, Silverman D, Garshick E, Vlaanderen J, Portengen L, Steenland K (2014) Exposure-response estimates for diesel engine exhaust and lung cancer mortality based on data from three occupational cohorts. *Environ Health Perspect 122*(2):172–177. https://doi.org/10.1289/ehp.1306880

Vouitsis I, Taimisto P, Kelessis A, Samaras Z (2014) Microenvironment particle measurements in Thessaloniki, Greece. *Urban Climate*, *10, Part 4*:608–620. https://doi.org/10.1016/j.uclim.2014.03.009

Weichenthal S, Van Ryswyk K, Kulka R, Sun L, Wallace L, Joseph L (2015) In-vehicle exposures to particulate air pollution in canadian metropolitan areas: the urban transportation exposure study. *Environ Sci Technol 49*(1):597–605. https://doi.org/10.1021/es504043a

Williams RD, Knibbs LD (2016) Daily personal exposure to black carbon: a pilot study. *Atmos Environ 132*:296–299. https://doi.org/10.1016/j.atmosenv.2016.03.023

World Health Organisation. (2012). *Health Effects of Black Carbon* (p. 86). http://www.euro.who.int/en/publications/abstracts/health-effects-of-black-carbon-2012

Wu S, Deng F, Niu J, Huang Q, Liu Y, Guo X (2011) Exposures to PM2.5 components and heart rate variability in taxi drivers around the Beijing 2008 Olympic Games. *Sci Total Environ 409*(13):2478–2485. https://doi.org/10.1016/j.scitotenv.2011.03.034

Yang F, Kaul D, Wong KC, Westerdahl D, Sun L, Ho K, Tian L, Brimblecombe P, Ning Z (2015) Heterogeneity of passenger exposure to air pollutants in public transport microenvironments. *Atmos Environ 109*:42–51. https://doi.org/10.1016/j.atmosenv.2015.03.009

Zhang Q, Zhu Y (2010) Measurements of ultrafine particles and other vehicular pollutants inside school buses in South Texas. *Atmos Environ 44*(2):253–261. https://doi.org/10.1016/j.atmosenv.2009.09.044

Zuurbier M, Hoek G, Oldenwening M, Lenters V, Meliefste K, van den Hazel P, Brunekreef B (2010) Commuters' exposure to particulate matter air pollution is affected by mode of transport, fuel type, and route. *Environ Health Perspect 118*(6):783–789. https://doi.org/10.1289/ehp.0901622