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Taxi drivers' exposure to black carbon and nitrogen dioxide in electric and diesel vehicles: A case study in London

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ABSTRACT

Nitrogen dioxide (NO_2) and black carbon (BC) concentrations were measured inside London taxicabs across 40 work shifts in a real-world occupational study. The shifts were measured across five plug-in hybrid range-extender electric taxicabs (TXe City) and five diesel taxicabs (TX4 Diesel). The aim of this study was to characterise the impact of fuel and cabin design on professional drivers' air pollution exposures. Personal exposure was monitored using portable BC, NO_2 and GPS devices. A controlled study replicating a typical taxi drivers' route in central London was conducted. Simultaneous inside and outside BC concentrations were measured to assess infiltration rates. The drivers were instructed to keep the BC devices with them at all times, providing a comparison of exposures at work and outside of work. The driver's average BC and NO_2 exposure while working was nearly twice as high for diesel taxicab drivers (6.8 ± 7.0 μg/m^3, 101.9 ± 87.8 μg/m^3) compared with electric drivers (3.6 ± 4.9 μg/m^3, 55.3 ± 53.0 μg/m^3, respectively). The exposure to BC while not working was 1.6 μg/m^3 for diesel drivers and 1.1 μg/m^3 for electric drivers, highlighting the very high exposures experienced by this occupational sector. The analysis of vehicle type on BC concentrations showed that the airtight cabin design and presence of an in-built filter in the electric TXe City reduced the exposure to BC substantially; indoor to outdoor ratios being 0.63 on the electric taxi compared to 0.99 on the diesel taxi with recirculate ventilation mode off and 0.07 to 0.44 with recirculate on. These findings provide important evidence for occupational health of professional drivers through exposure reduction measures in vehicle design.

1. Introduction

The health effects of traffic-related pollutants such as black carbon (BC), which is a component of fine particulate matter ($PM_{2.5}$), and nitrogen dioxide (NO_2), are well documented (COMEAP, 2015). As BC has no non-combustion sources, is primarily emitted by diesel vehicles and is chemically stable, it is well suited as a tracer for vehicle emissions (Invernizzi et al., 2011). Additionally, studies have found that there are more adverse health effects associated with exposure to the BC fraction, compared to total particulate matter mass (Janssen Nicole et al., 2011). Further, the TRAFFIC studies in London found that short-term exposure to BC was associated with increased respiratory and cardiovascular hospital admissions and respiratory mortality (Samoli et al., 2016; Atkinson et al., 2015).

Existing studies on driver exposure to air pollution have indicated that people travelling in vehicles are among the highest exposed and that fixed monitoring sites do not adequately describe driver exposure (Li et al., 2015; Knibbs et al., 2011). Furthermore, concentrations inside taxicabs were found to be higher than concentrations in buses, trains, and other active transport methods (Hachem et al., 2019), making this a concern for both drivers and passengers. Results from several panel studies indicate that health effects such as pulmonary inflammation, oxidative stress, and changes in heart rate were induced by increased in-vehicle pollution concentrations (Shields et al., 2013; Wu et al., 2010; Sarnat et al., 2014). Additionally, a study on taxi drivers found that impaired vascular health due to amplified atherogenesis could result from long-term occupational exposure to air pollution (Brucker et al., 2014).

Few studies have characterised exposures of traffic-related air pollution on taxi drivers. A review on exposure to traffic related

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pollutant in taxicabs by Hachem et al. (2019) included only one study with measurements of NO_2 and one with measurements of BC (Son et al., 2004; Gany et al., 2017). No study measuring both pollutants was found. One study that has measured in-cabin concentrations of NO_2 found significantly higher concentrations in diesel vehicles than in petrol vehicles in a comparison of taxi driver and non-occupational driver exposures using passive samplers (Son et al., 2004).

Previous research indicates that filters on a vehicle's air intake could reduce particulate matter concentrations in the cabin, and that the recirculation setting reduces the particle number concentrations inside passenger cars, with the effect being greater in newer vehicles (Tartakovsky et al., 2013). An analysis of $PM_{2.5}$ and ultra-fine particles (UFP) in Los Angeles taxicabs found that keeping the windows closed and operating a HEPA filter reduced indoor-outdoor ratios of both pollutants significantly. Additionally, indoor concentrations largely followed outdoor concentrations when windows were kept open (Yu et al., 2018). A study conducted in Barcelona comparing diesel and non-diesel taxi pairs found that air exchange rates were the dominant influence on vehicle indoor air quality (Moreno et al., 2019), indicating that vehicle type could be an important determinant of exposure. Encountering diesel vehicles on the road lead to large increases in in-vehicle concentrations of BC, $PM_{2.5}$ and UFP in a commuter study in Canada, with indoor-outdoor ratios rising by over 15% (Weichenthal et al., 2015). The potential health effects of traffic-related air pollution to drivers necessitate a better understanding of both exposure levels and their determinants within this occupational group. Furthermore, the effect of vehicle type and cabin design on driver exposure in the real-world occupational environment have not been characterised extensively.

This study was formulated to fully characterise taxi drivers' exposures under real-world urban driving conditions, performing measurements in the electric TXe City and TX4 Diesel taxis. To the authors knowledge, in-cabin concentrations of BC and NO_2 in London taxicabs had not been measured prior to this study. There are 108,000 licensed taxi and private hire vehicles in London, making up 4.2% of total vehicle numbers (DEPARTMENT FOR TRANSPORT, 2019), with the proportion likely to be much higher in congested central London. Workplace Exposure Limits (WEL) are in place in the UK, with a maximum exposure of 0.96 mg/m^3 for NO_2 and 3.5 mg/m^3 for BC over an 8-h time weighted average period being allowed. Neither of these limits were reached in this study (HSE, 2020). A follow-up controlled experiment was conducted simultaneously measuring BC inside and outside the vehicle cabin to understand infiltration rates and better explain the differences in concentrations measured in the two vehicle types. Moreover, this study aimed to further clarify the impact that vehicle fuel type and cabin design have on the exposure of professional drivers. The comparison between diesel vehicles and electric vehicles is particularly important, as diesel vehicles are one of the primary emitters of BC and NO_2 in the UK while electric vehicles emit neither (Carslaw and Rhys-Tyler, 2013; Lau et al., 2015) and are therefore being promoted to drivers as a desirable alternative.

2. Methods

2.1. Study design

2.1.1. Taxicab driver exposure

Ten professional taxicab drivers were recruited by the London Electric Vehicle Company (LEVC). The drivers were equipped with GPS-linked BC monitors, micro aethalometers (MA350, Aethlabs, CA, USA), and AQmesh pods (Environmental Instruments Ltd., UK), which measures a variety of gaseous pollutants. This study only utilised the NO_2 measurements made by the AQmesh pods. All measurements were continuous and logged at 1-min resolution. Due to the recent development of the MA350s in 2016 there have been few studies that have used this device, however its predecessor, the microAeth AE51, has been utilised and evaluated in previous studies (Ferrero et al., 2011; Gany et al., 2017). The AQmesh pods have been used throughout London and are one of the few portable sensors that measure NO_2. Due to their size and weight, the AQmesh was kept in the vehicle cabin throughout the sampling period, and the MA350 was carried by the drivers outside of working hours. The drivers were instructed to keep the BC monitors with them wherever they went, except at night, when the unit was put on charge. This allowed for characterization of the difference in the driver's BC exposure at work and outside of work. Of the ten drivers five drove diesel vehicles, type London Taxi Company (LTC) TX4, built between the years 2008 and 2016. The other five drove plug-in hybrid range-extender electric vehicles, model LEVC TXe City, built in 2018. While the design of the taxis is substantially different, the taxis were essentially made by the same company as LTC rebranded to LEVC in 2017.

Measurements were taken over three weeks between 21 May to 8 June 2018. All drivers were non-smokers, to avoid interference with measurements (You et al., 2015). The drivers were instructed to keep the instruments away from smokers during the measurement period, and to note any interference that might have occurred. A questionnaire on shift-details such as the number of work hours was handed out to each driver, which was filled in after each shift during the sampling period. Exposure data were collected during four working days per driver. The drivers were asked to close their windows and set the ventilation to recirculate mode during the first two days to allow fair comparison between vehicle types, with free reign on the latter two days to better reflect typical occupational exposure. In total over 1100 h of exposure data were analysed. Three drivers were not able to record all four work shifts for BC data due to the monitor not being sufficiently charged. Despite this, 36 full work shifts (out of 40) were analysed for BC. 40 out of 40 work shifts were analysed for NO_2. All measured working days were weekdays, except for a single shift worked on a weekend. Working hours were mostly between 8 am and 10 pm and all drivers worked in central London only.

2.1.2. Assessing air exchange rates between vehicle types

To further understand the differences between in-cabin exposure experienced in diesel and electric taxis, a follow up controlled study was run simultaneously measuring inside and outside cabin black carbon concentrations at 1-min resolution (using MA350s) on a typical taxi route in central London. This provided data to characterise infiltration of traffic related pollutants into the vehicle cabin and thus the different exposures experienced by drivers (Yu et al., 2018). One TXe City and one TX4 Euro 5 diesel taxi were used in this study (further details in Supporting Information). Both taxis were fully licensed, working London taxis that had recently been serviced.

A circular test route of 7.1 km typically traversed by taxi drivers in Central London was selected (Figure A2). Each taxi drove the route four times, twice with ventilation set to recirculate and twice with recirculate off. Fan speed was set on at medium speed with windows closed for all runs. Four further runs with the electric taxi pollen filter removed were driven with recirculate on and off to investigate the effectiveness of the pollen filter in reducing in-cabin concentrations. The diesel taxi was designed without a filter so this test could not be run on this vehicle. The tests were run over two days on 13th and 14^{th} of May 2019 with the electric and diesel taxis being tested on both days. Overall a total of 12 runs were conducted lasting approximately 35 min each (four with the diesel taxi, four with the electric taxi with filter in and four with electric taxi without filter). Unfortunately, two of the runs had to be discarded as the monitors malfunctioned during the run. Despite this, 10 runs were available for analysis.

2.2. Instrument calibration

The AQmesh pods were co-located at Marylebone Road reference monitoring station for 11 days prior to and 7 days after the experiments, whereas the MA350s were only co-located after sampling due to time restrictions. Correction factors were calculated using standard major axis regression of raw monitor data against scaled reference monitor data and applied to the dataset. The correction factors and a more detailed description of the co-location process is in Supporting Information (Figure A1).

2.3. Data processing

Noise and sampling artefacts can be an issue for BC measurements taken at a high frequency. To resolve this, the data were processed using the Optimized Noise-reduction Averaging (ONA) algorithm (Hagler et al., 2011).

2.4. Statistics

In order to assess whether differences between daily average exposures for each vehicle and differences between the work environment and the outside of work environment were statistically significant, a Mann-Whitney-Wilcoxon test was utilised. The Mann-Whitney-Wilcoxon test was also used to test whether the differences between outside of work exposures of diesel vehicle drivers and electric vehicle drivers were statistically significant. A mixed-effects model was used to determine whether background concentrations, vehicle type, and temporally varying factors such as wind speed and temperature had a significant effect on cabin concentrations of BC and NO_2. 98th percentiles were calculated to illustrate peaks and the highest pollutant concentrations that drivers are exposed to.

3. Results

3.1. Exposure at work and outside of work for electric and diesel taxi drivers

Driver exposure was highly variable between individuals, with average exposures per shift at work ranging between 2.4 and 11.6 μg/m^3 for BC and 38.9–123.3 μg/m^3 for NO_2 (Table A1). The highest exposed driver for BC was also exposed to the highest levels of NO_2. This was also observed for the driver with the lowest exposure. The drivers' exposures to BC while working were three times higher than outside of work for the TXe City vehicle drivers, and four times higher at work than outside of work for the diesel vehicle drivers (Table 1). The difference between daily average exposures at work compared with outside of work exposures (Wilcoxon test; $p < 0.01$) was statistically significant. The average exposures to BC for all drivers at work were 5.2 (6.0) μg/m^3 compared with 1.4 (2.8) μg/m^3 outside of work (Table A1).

A mixed-effects model determined that the air temperature had a negligible but statistically significant effect on cabin concentrations of BC and NO_2 ($p < 0.01$ and $p < 0.05$, respectively). The wind speed similarly barely affected BC concentrations but had a slightly stronger effect on NO_2 concentrations ($p < 0.01$ and $p < 0.05$, respectively). Background concentrations of both NO_2 and BC had a statistically significant yet minor effect on concentrations ($p < 0.001$). The vehicle type was found to be a major determinant of cabin concentrations for both pollutants measured ($p < 0.05$) (Figure A3 & A4).

The difference between exposures for each vehicle type were statistically significant ($p < 0.001$). Mean exposure to BC at work at 1-min resolution was nearly twice as high for diesel vehicle drivers (Table 1). 98th percentiles at work were highest for TX4 Diesel taxi drivers at 25.5 μg/m^3 compared with 15.9 μg/m^3 for TXe City vehicle drivers. 98th percentiles were also higher for TX4 Diesel taxi drivers outside of work (Table 1). The range of exposure concentrations for TX4 Diesel taxi drivers were much larger, with the median exposure being 2.4 μg/m^3 higher than for the electric vehicle drivers (5.3 μg/m^3 compared with 2.9 μg/m^3) (Fig. 2).

The difference in exposure to NO_2 between diesel and electric vehicle drivers were similar (Table 1). Average exposure to NO_2 among the diesel vehicle drivers was nearly twice as high as among electric vehicle drivers. The 98th percentiles were very similar outside of work, with marginally higher exposure for TX4 Diesel taxi drivers. At work the 98th percentiles were significantly higher for TX4 Diesel taxi drivers. The boxplots for NO_2 exposure at work illustrated different patterns of exposure, with a larger range and a higher median of 95.7 μg/m^3 for TX4 Diesel taxi drivers and a smaller range and a lower median of 45.3 μg/m^3 for TXe City electric taxi drivers (Fig. 3).

Concentrations of BC and NO_2 were found to be higher outside of work for TX4 Diesel drivers, with a mean of 1.6 μg/m^3 compared with 1.1 μg/m^3 and 30.1 μg/m^3 compared with 22.2 μg/m^3, respectively ($p < 0.001$). These values were between 2 and 4 times lower compared to mean at work exposures (Table 1). While these differences are significant, the absolute differences between the electric and diesel drivers were substantially lower than the at work exposures.

Fig. 1 shows a same-day comparison of exposure to BC on a typical driving day in London between a TX4 Diesel and a TXe City electric vehicle. The diesel vehicle driver is exposed to a higher concentration of BC at almost every point, and is exposed to higher peaks, with the highest peak ranging up to 68.8 μg/m^3, and many peaks between 20 and 50 μg/m^3. The highest BC concentration measured in the electric vehicle reached 22.3 μg/m^3. It is hypothesized that these peaks in exposure were caused by individual events where the vehicle cabin was infiltrated by pollutants from a direct local source, such as following a high polluting vehicle, or when transiting through a congested street canyon.

3.2. Infiltration rate analysis

Table 2 presents the summary results of each run for the controlled study. The results show average concentration was higher inside diesel taxis compared to electric taxis both with and without the filter. Unfortunately, only one run was completed with recirculate set to off for the inside-outside analysis in the diesel taxi and this run coincided with very high outside readings compared to the other runs, which resulted in

Table 1
Summary statistics of driver exposure to nitrogen dioxide and black carbon at 1-min resolution while outside of work. Standard deviation (sd) is the variation in the drivers' exposure at 1-min resolution.

Driver status	Driver's vehicle type	Mean (sd) nitrogen dioxide exposure (μg/m^3)	Mean (sd) black carbon exposure (μg/m^3)	Median (iqr) nitrogen dioxide exposure (μg/m^3)	Median (iqr) black carbon exposure (μg/m^3)	98th percentile NO_2 exposure (μg/m^3)	98th percentile BC exposure (μg/m^3)	Vehicle type	Emission Standard
At work	Electric	55.3 (53.0)	3.6 (4.9)	45.3 (51.1)	2.9 (2.7)	164.3	15.9	TXe City	Zero Emission
	Diesel	101.9 (87.8)	6.8 (7.0)	95.7 (61.9)	5.3 (5.9)	211.7	25.5	TX4 Diesel	Euro 4 - 6
Outside of work	Electric	22.2 (36.4)	1.1 (1.7)	19.4 (17.9)	1.0 (0.9)	133.4	5.2	TXe City	Zero Emission
	Diesel	30.1 (42.2)	1.6 (3.1)	26.6 (23.5)	1.4 (1.4)	140.7	8.6	TX4 Diesel	Euro 4 - 6

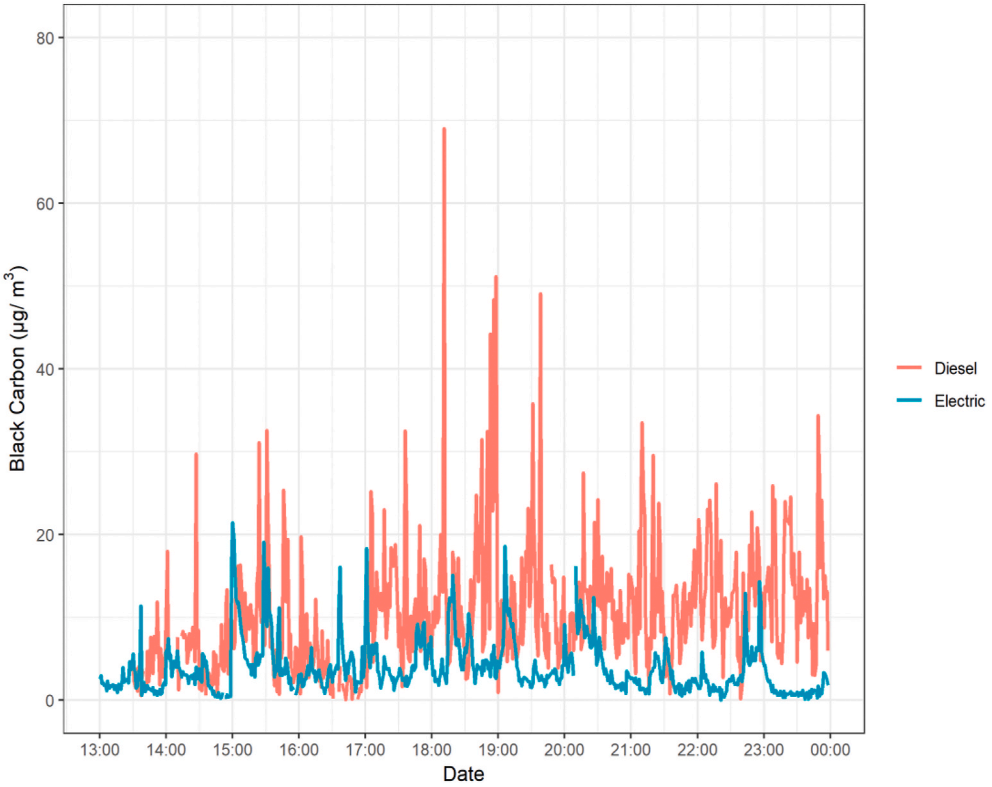

Fig. 1. Chart showing a same-day comparison on a typical driving day of exposure to black carbon in a TX4 Diesel vehicle and a TXe City electric vehicle, 31st of May 2018.

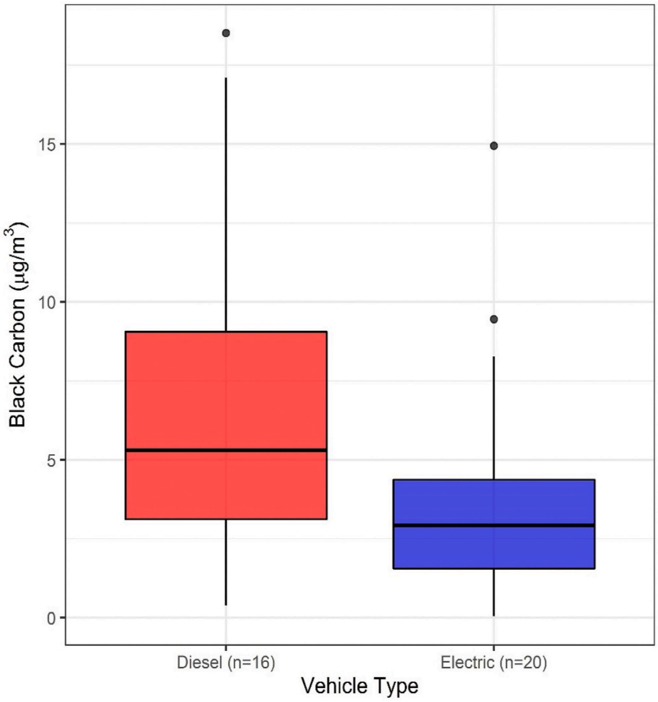

Fig. 2. A boxplot showing the exposure to BC depending on vehicle type during 16 shifts for diesel vehicles and 20 shifts for the electric vehicles. The centrelines represent medians, with the upper quartile (Q3) above and the lower quartile (Q1) below.

higher inside readings. It is likely that without this run, absolute in-cabin diesel taxi concentrations would be like the electric taxi without the filter, with the electric taxi with the filter resulting in the lowest in-cabin concentrations. Time series examples of the runs are presented in Fig. 4 and the exact route driven can be found in Figure A2.

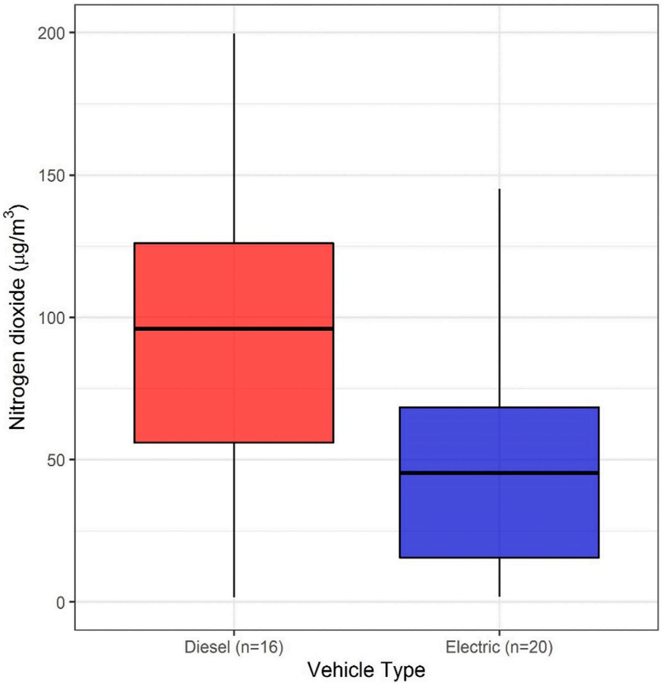

Fig. 3. A boxplot showing the exposure to NO_2 depending on vehicle type during 16 shifts for diesel vehicles and 20 shifts for the electric vehicles. The centrelines represent medians, with the upper quartile (Q3) above and the lower quartile (Q1) below.

Table 2
Summary statistics of runs for paired inside and outside 1-min black carbon concentrations in a Diesel taxi and Electric taxi with and without its filter.

Ventilation mode	Diesel taxi				Electric taxi with filter (i.e. standard setup)				Electric taxi without filter			
	Time per run *Minutes*	Inside *Mean (sd) black carbon exposure (μg/ m^3)*	Outside	Inside/ Outside *Ratio*	Time per run *Minutes*	Inside *Mean (sd) black carbon exposure (μg/ m^3)*	Outside	Inside/ Outside *Ratio*	Time per run *Minutes*	Inside *Mean (sd) black carbon exposure (μg/ m^3)*	Outside	Inside/ Outside *Ratio*
Recirculate on run 1	34.0	0.7 (0.4)	1.7 (1.5)	0.43	35.0	0.3 (0.2)	2.1 (2.6)	0.15	32.0	1.0 (0.4)	1.3 (1.3)	0.75
Recirculate on run 2	39.0	0.9 (0.5)	2.0 (1.7)	0.46	40.0	0.0 (0.3)	2.2 (2.8)	0.00	37.0	0.9 (0.2)	1.1 (0.7)	0.85
Recirculate on average	**36.5**	**0.8 (0.4)**	**1.8 (1.6)**	**0.44**	**37.5**	**0.2 (0.2)**	**2.2 (2.7)**	**0.07**	**34.5**	**1.0 (0.3)**	**1.2 (1.0)**	**0.80**
Recirculate off run 1	33.0	7.4 (12.6)	7.4 (11.4)	0.99	35.0	0.6 (0.4)	0.7 (0.4)	0.92	37.0	1.8 (1.1)	1.8 (1.4)	0.95
Recirculate off run 2	–	–	–	–	42.0	0.3 (0.4)	1.0 (0.9)	0.32	–	–	–	–
Recirculate off average	**33.0**	**7.4 (12.6)**	**7.4 (11.4)**	**0.99**	**38.5**	**0.5 (0.4)**	**0.9 (0.7)**	**0.63**	**37.0**	**1.8 (1.1)**	**1.8 (1.4)**	**0.95**
	35.3	**3.0 (4.5)**	**3.7 (4.8)**	**0.62**	**36.9**	**0.3 (0.3)**	**1.5 (1.7)**	**0.56**	**36.9**	**1.2 (0.6)**	**1.4 (1.1)**	**0.86**

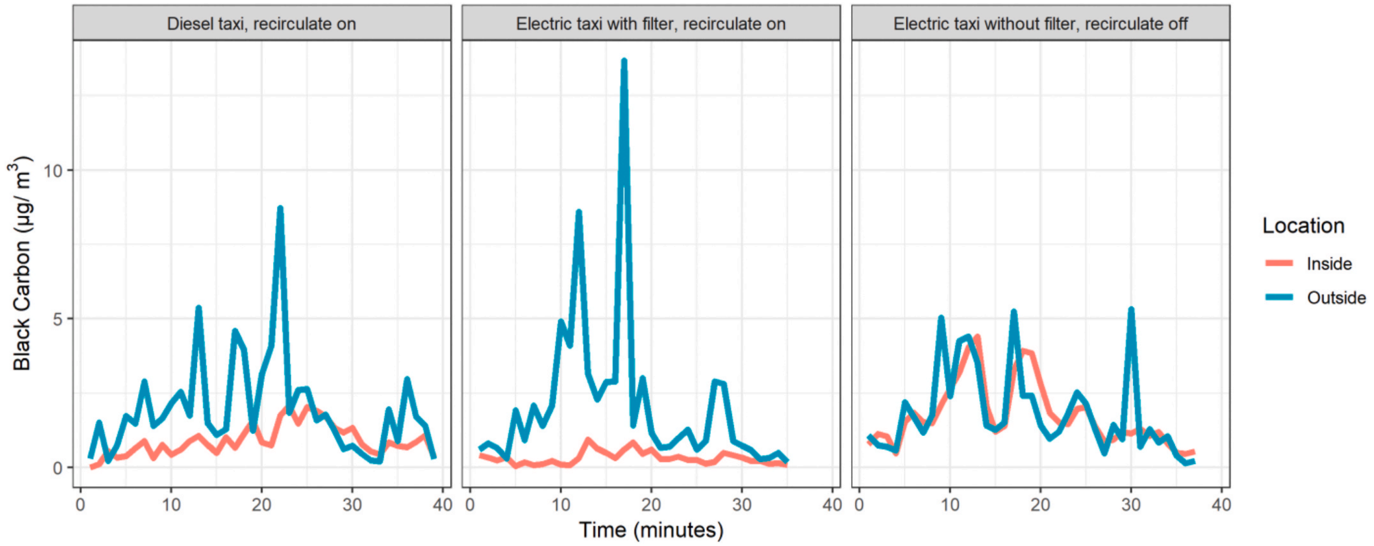

Fig. 4. Paired inside and outside 1-min black carbon concentrations for diesel taxi with recirculate on; electric taxi with filter, recirculate on and electric taxi without filter, recirculate off.

When set to recirculate the inside to outside (I/O) ratio was 0.44 compared to 0.99 with recirculate off in diesel taxis while in electric taxis with the filter in, recirculate reduced exposure to negligible levels with the I/O ratio being 0.07 compared to 0.63 with recirculate off. There is a larger uncertainty regarding the reduced infiltration of outside pollutants in the electric taxi with recirculate off as the ratios were substantially different for the two runs (0.32 and 0.92). Nonetheless the results suggest that the electric taxi cabin reduced the infiltration of outside black carbon concentrations compared to diesel taxis. Of further interest is the effectiveness of the pollen filter in reducing exposures in the electric taxi, as when this was removed the I/O ratio was on average 0.85 and similar to the ratios observed for the runs in the diesel taxi. Furthermore, these ratios were worse compared to runs in diesel taxis when the ventilation was set to recirculate.

4. Discussion

In this study we hypothesized that taxi drivers using electric vehicles would have lower exposures to diesel fumes than diesel taxi drivers. Secondary objectives included establishing the determinants of any observed differences in exposures by assessing infiltration rates and concentrations inside two different vehicle types and evaluating the impact of fuel type and cabin design on exposures. This study confirms that taxi drivers are exposed to very high levels of traffic-related pollution while at work, compared to outside of work and typical population exposures; average BC work exposures being 5.1 μg/m^3, three to four times higher than outside of work exposures. Further, it was found that different vehicle types could reduce exposures experienced by drivers. The fact that mean BC and NO_2 exposures while driving were nearly twice as high for diesel taxis compared to electric has important implications in reducing exposures for these drivers. Major effects on cabin concentrations by weather variables such as temperature and wind speed were ruled out by a mixed-effects model. Background concentrations of pollutants did affect cabin concentrations, however, the effects were minor. The model confirmed the fact that the vehicle type had a strong effect on BC and NO_2 concentrations. Other studies have found average exposures of 1.4 μg/m^3 for workers in offices (Dons et al., 2011) and 1.6 μg/m^3 for children at schools (Paunescu et al., 2017). Gany et al. (2017) found lower mean BC concentrations to our study ranging between 1.8 and 3.4 μg/m^3 in New York taxicabs (petrol), though variability was high. Moreno et al. (2019) found median exposures for BC taxis at 6.5 μg/m^3 in Barcelona further confirming the high pollution taxi drivers face in their day to day work. The only comparable study investigating NO_2 concentrations in taxicabs was conducted in 2004. Son et al. (2004) found lower NO_2 concentrations than our study did, with higher cabin concentrations of NO_2 in diesel taxis than in petrol taxis (72.9 ± 2.5 μg/m^3 and 50.3 ± 2.5 μg/m^3).

The biggest indication on the cause of the difference in driver exposure is the improved cabin design of the electric TXe City taxis. The infiltration rate analysis showed that recirculating the air inside the taxi and having a pollen filter substantially reduced the drivers' exposure to BC. Furthermore, the I/O ratio was 0.99 in the diesel taxi with recirculate off, and 0.44 with recirculate on, indicating that BC concentrations inside and outside of the taxicab were virtually the same before the recirculate setting was turned on. In the electric vehicle, even with recirculate off the I/O ratio was 0.63, lower than in the diesel vehicle. Turning on recirculate reduced the ratio further to 0.07, barely detecting BC concentrations inside the vehicle. The pollen filter appeared to contribute to a large share of this change in infiltration. Vehicles in other studies have also been shown to have lower PM concentrations in recirculation mode (Tartakovsky et al., 2013). Yu et al. (2018) found similar I/O ratios between 0.52 and 0.82 for taxicabs with windows closed and using HEPA filters for $PM_{2.5}$, although they did not observe the very low ratios that were experienced in the electric taxicabs when recirculate was turned on.

Whilst closing windows and using air recirculation has been shown to reduce in cabin pollution concentrations, this benefit needs to be viewed against the potential detrimental impacts of increased carbon dioxide (CO_2) within the vehicle. CO_2 originating from the driver's breath can accumulate rapidly within the cabin of the vehicle where elevated concentrations have been shown to cause fatigue and loss of concentration (Barnes et al., 2018; Hudda and Fruin, 2018). Hudda and Fruin found CO_2 levels in vehicles could get above 2500 ppm in as little as 15 min. It is therefore advisable that recirculate mode is used in congested areas to protect passengers from the infiltration of ambient pollutants, however the cabin also needs to be periodically ventilated when outside of these areas to avoid adverse CO_2 accumulation.

Tartakovsky et al. (2013) suggested PM levels could be lower in newer vehicles. The reasons for this could be reduced air exchange rate or improved air-filtration systems, both of which appear to be the case in the TXe City taxi. Self-pollution in the case of the diesel vehicles could also lead to higher BC values inside the cabin. Marshall and Behrentz showed self-pollution in school buses can contribute significantly to pollution concentrations inside the vehicle (Marshall and Behrentz, 2005). In the case of taxis, a recent study found higher BC and carbon monoxide (CO) concentrations inside diesel taxis when compared with non-diesel taxis and larger UFP sizes, possibly indicating self-pollution (Moreno et al., 2019). However, it was not clear whether the cabin design and air exchange rates of the vehicle pairs was the same. In this study, concentrations of BC measured outside the electric and diesel vehicles were similarly high, indicating that self-pollution may not be a significant factor in determining BC concentrations in diesel vehicles.

The higher outside of work exposures of the TX4 Diesel drivers might be explained by different behaviour during non-work hours. A simple reason such as proximity to major roads of the TX4 Diesel drivers' residences could explain this difference, however, any type of activity close to combustion sources or the drivers driving their taxicab outside of work hours could be responsible for this difference. But as activities outside of work were not tracked, we were not able to identify the reasons for the higher outside of work exposure of the TX4 Diesel drivers. In future studies, having the drivers keep a diary of activities during non-work hours would be useful to track and explain non-work-related exposures.

The fact there are simple changes that taxi drivers can enact to reduce exposure, such as careful selection of vehicle type and changes to ventilation settings, is important as adverse health effects have been observed to decrease with declining levels of pollution even over short periods of time (Schraufnagel et al., 2019; Gauderman et al., 2015). Furthermore, if more drivers move from diesel to electric taxis this will not only reduce drivers' exposures to traffic-related air pollution but also reduce ambient pollution levels.

4.1. Limitations

This study had several shortcomings. First, more robust results would have been achieved with a greater number of subjects, particularly in the controlled study; data were highly variable, and a larger dataset would have allowed a more comprehensive interrogation of the basis for this variability. Despite this, over 1100 h of data were collected in one of the largest real-world professional drivers' studies to date. Second, a time resolved method of recording ventilation settings would allow greater confidence in partitioning exposures. It is likely that this would have to be automated due to participant burden. Alternatively, a proxy such as in-cabin CO_2 concentrations could have been used.

5. Conclusions

It is clear from this study that cabin design and the presence of filters are important in reducing traffic-related pollution exposures to drivers. This is particularly important to professional drivers, who spend a large portion of their working lives in this polluted environment. It is likely that a diesel taxi with a similar cabin design and filter as the electric taxi would result in the drivers experiencing similar levels of exposure, therefore suggesting that fuel type does not play a significant part in the reduced exposures. Vehicle ventilation set to recirculate also reduces pollution exposure substantially but requires balancing against possible negative cognitive responses related to the buildup of CO_2 in the vehicle. Despite our study suggesting that fuel type did not play a significant part in reducing drivers' exposures, the most effective way to reduce all drivers' exposures to traffic related air pollution would be to change to zero tailpipe emission vehicles with airtight cabins and filters. This will not only reduce drivers' exposures but also reduce ambient concentrations which will provide health benefits to the drivers and the general population.

Credit author statement

Brendan Bos: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Visualisation, Writing – original draft, Writing – review & editing. Shanon Lim: Conceptualization, Methodology, Data curation, Writing- Review & Editing, Formal analysis. Michael Hedges: Investigation, Formal analysis, Writing – original draft, Formal analysis, Data curation. Nick Molden: Methodology, Writing – review & editing. Sam Boyle: Investigation. Dr Ian Mudway: Supervision, Writing – review & editing, Conceptualization, Project administration, Funding acquisition.: Dr Benjamin Barratt: Supervision, Writing- Reviewing and Editing, Conceptualization, Project administration, Funding acquisition.

Declaration of competing interest

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

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Appendix A. Supplementary data

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