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Evaluating real-world emissions from in-use buses and taxis using on-road remote sensing ☆

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ABSTRACT

Assessing real-world emissions from buses and taxis is vital to comprehend their impact on urban air quality. Such vehicles differ significantly from the majority of the fleet owing to their higher mileage rates. However, few studies have focused on specifically assessing the emissions from this segment of the vehicle fleet. In this context, this study evaluated the real-world emissions of nitrogen oxides (NO_x) from in-use buses and taxis in Dublin, Ireland, using crossroad remote sensing technology. The remote sensing system was deployed at strategic locations throughout the city to capture on-road emissions from passing vehicles. The collected data included vehicle related information such as emission standard, make, and mileage, and pollutants including NO_x. Based on this data, analysis was aimed to understand the impact of Euro emission standard, ambient temperature, mileage, and make of the vehicle on NO_x emissions. The results reveal that the average emissions from taxis reduce by 37% from Euro 5 to Euro 6b, and average emissions from Euro 6 buses are 87% lower compared to Euro 5. The trends in emission factors (EFs) of buses and taxis were similar during summer and winter sampling. Moreover, on comparing the emissions from the top five taxi manufacturers, different trends in the emission factors were observed. Finally, the study found that the effect of vehicle mileage on emissions was unclear for both buses and taxis. In any case, these findings provide valuable insights into the real-world emission performance of the existing fleet of buses and taxis in Dublin and highlight the need for targeted measures to reduce emissions from these vehicles. The results can assist policymakers and urban planners in formulating evidence-based strategies to improve air quality in Dublin and other cities facing similar challenges.

1. Introduction

With the rapid growth in urbanisation and reliance on fossil fuel-based motor vehicles, air quality has become a significant concern in urban areas (Tang et al., 2020; Huang et al., 2021). The combustion of gasoline and diesel fuels in vehicles releases a range of pollutants, including particulate matter (PM), nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds. These pollutants have significant detrimental effects on human health, leading to respiratory diseases and other related illnesses with severe implications on children and older adults (Tang et al., 2020). As the number of vehicles on the roads continues to rise, the need to address and mitigate air quality problems becomes crucial. To reduce the environmental pollution from new vehicles, European vehicular emission standards, also known as Euro emission standards, have been implemented. These standards have evolved from Euro 1 in 1992 to the recent Euro 6d in 2021 (Singh et al., 2023). Further, the upcoming Euro 7 standards impose even stricter limits on permissible emissions from new vehicles (European Commission, 2022).

In Ireland, transport is the second-largest contributor of NO_x emissions, accounting for approximately 33.8% of the total emissions in 2021 (EPA, 2023). This includes a diverse group of vehicles such as

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passenger cars, taxis, motorcycles, vans, buses, and trucks. Past studies on vehicular emissions in general, and remote sensing-based studies in particular, have increasingly focused on passenger cars, possibly due to their significant share in the total vehicle fleet, and neglected other vehicle types such as buses and taxis.

Buses and taxis play a significant role in urban mobility by providing an affordable, reliable, and sustainable option for a range of commuters (Lawson et al., 2013). However, with their high mileage and prolonged operation within city limits, buses and taxis are an inherent environmental challenge (Geng et al., 2013; Mahesh and Ramadurai, 2017). Often powered by diesel engines, these vehicles emit substantial amounts of pollutants, which is particularly concerning as they frequently operate in densely populated urban areas (Dey et al., 2018). The concentration of harmful emissions in these areas can have severe consequences for air quality and public health due to the considerable number of people exposed. Therefore, understanding the specific contribution of buses and taxis to urban air pollution becomes crucial for implementing and evaluating strategies and policies aimed at improving air quality.

To accurately quantify and manage air pollution from on-road vehicles, it is necessary to develop reliable measurement techniques. Remote sensing technology has emerged as a promising approach for assessing real-world emissions from a large fleet of vehicles in a cost-effective manner (Carslaw and Rhys-Tyler, 2013b; Huang et al., 2018a). This technology utilises ultraviolet and infrared sensors to remotely measure the emissions from passing vehicles, including nitrogen oxides and particulate matter. By capturing emission data at the roadside, remote sensing offers a non-intrusive and efficient method for assessing the overall emission performance of on-road vehicles (Huang et al., 2018a).

Remote sensing (RS) techniques to measure tailpipe emissions from a fleet of in-use vehicles have been used in several studies worldwide. Carslaw and Rhys-Tyler (2013b) evaluated the emissions of NO_x, NO_2, and NH_3 from different vehicle types in London, United Kingdom and concluded that Selective Catalytic Reduction (SCR) systems did not have a significant effect in reducing NO_x emissions. In Hong Kong, Huang et al. (2018b) analysed the emissions based on engine size (or displacement) of the vehicle and reported a steady decrease in nitric oxide (NO) emissions of all vehicles during 2006-2016. Comparisons were also made between the RS measurements and near-road ambient concentrations. Mahesh et al. (2023) evaluated emissions from cars, vans, taxis, and buses in Dublin, Ireland and reported that emissions were significantly lower for Euro 6 vehicles. In Australia, Smit et al. (2019) carried out a simultaneous measurement of air quality and emissions and found a positive correlation between RS and air concentration for CO in calm conditions. Light Commercial Vehicles (LCVs) have been the focus of studies by Huang et al. (2019) and Chen et al. (2020) in Europe and Hong Kong, respectively. Chen et al. (2020) reported that EFs have gone down with the introduction of Euro 6a-b based on the data for LCVs in Sweden, Spain, Switzerland, and UK ranging from 2011-2018. Besides, the identification of high-emitting vehicles from the fleet has been the focus in recent studies (Hassani et al., 2021; Ghaffarpasand et al., 2023).

Despite the presence of several studies using remote sensing for emission estimation, studies which quantify emissions from in-use buses and taxis (Carslaw and Rhys-Tyler, 2013a; Zhang et al., 2021) are limited. One reason maybe due to the fact that the locations chosen for data collection may not have a significant volume of buses and taxis. Another reason could be that the study focuses on cars, and data from other vehicle types are not considered in the analysis. Thus, understanding of the emissions from buses and taxis using remote sensing is limited although it may be of a higher significance considering the high annual mileage and service life of these vehicles. Furthermore, buses and taxis tend to be particularly prevalent on certain road links in a city because of the routes and locations serviced, which is important for air quality in a city. This paper aims to address this gap in the understanding of real-world NO_x emissions from in-use buses and taxis based on data collected from a recent remote sensing campaign in Dublin, Ireland. While other pollutants were also measured, the focus of this paper is on NO_x due to its significant impact on air quality in urban regions.

The contributions of this paper can be summarised as follows: (1) This study quantifies and assesses emissions from a large number of in-use buses and taxis, including vehicles compliant with the latest emission standards (Euro 6d-temp and Euro 6d). Previous studies mainly focused on older Euro 3, Euro 4, and Euro 5 compliant vehicles. (2) The paper provides insights from a detailed analysis of a remote sensing-based emission dataset. Factors such as Euro emission standard, mileage, make, season, and ambient temperature are considered. The study also highlights the limitations of using vehicle age as a proxy for mileage. (3) The findings contribute to a better understanding of emissions from in-use buses and taxis, which is of relevance to other European cities with similar vehicle fleets. The results are also relevant for companies that own and manage bus or taxi fleets, helping them assess their environmental impact and develop long-term plans for reducing emissions.

2. Methods

This section presents the details of the on-road remote sensing setup, the instrument used, and the procedure adopted for data collection and preprocessing. The section also presents the details of the data analysis process.

2.1. Remote sensing setup

In the present study, multiple sites were selected to capture the vehicle fleet composition in Ireland, representing both sub-urban and urban traffic conditions. The focus was on single-lane roads with a gentle incline and high traffic volume. The preference for single-lane roads is to effectively separate the remote sensing measurements of individual vehicles and accurately attribute emissions to them individually (Borken-Kleefeld, 2013). Additionally, the choice of roads with a gentle incline aimed at capturing vehicle emissions during the acceleration phase, while the inclusion of roads with higher traffic volume facilitated conducting a larger number of individual vehicle tests (Bishop and Stedman, 2008). In total, six sites were chosen for conducting the study, as shown in Fig. 1. However, out of these six sites, most of the data was collected from three sites (Beach Road, College Green, and Templeogue Road) due to higher traffic volume and overall suitability of the site. The pie charts shown illustrate the distribution of data collected for buses and taxis across various sites, presented as percentages. Table 1 shows the latitude and longitude, gradient, mean speed, and the total number of tests conducted for buses and taxis. The road gradient at different sites varied from 0% to 5.2%. The lowest mean speed was observed on College Green for both buses (19.0 km/h) and taxis (22.4 km/h). The highest mean speed was observed on Chapelizod Hill Road for taxis (35.0 km/h) and Templeogue Road for buses (33.2 km/h). College Green was located on a roadway which was not open to private passenger car traffic and therefore the majority of vehicles at this location were buses and taxis, while at other locations buses and taxi sampling was conducted in mixed traffic.

An OPUS AccuScan RSD 5000 instrument was used for data collection. The instrument consists of multiple modules that activate simultaneously, including an Ultraviolet (UV) and non-dispersive Infrared (IR) source and detector, a reflector, optical speed-acceleration bars to capture instantaneous driving conditions, a camera to take an image of the rear view of the vehicle and its registration number, and multiple sensors to record the ambient temperature (°C), pressure, and relative humidity. The UV and IR source/ detector and reflector were set at a level of 20 cm, which is approximately equal to the tailpipe level of most light-duty vehicles. When a vehicle passes the instrument setup, an emissions snapshot is captured with details including the concentrations of different pollutants.

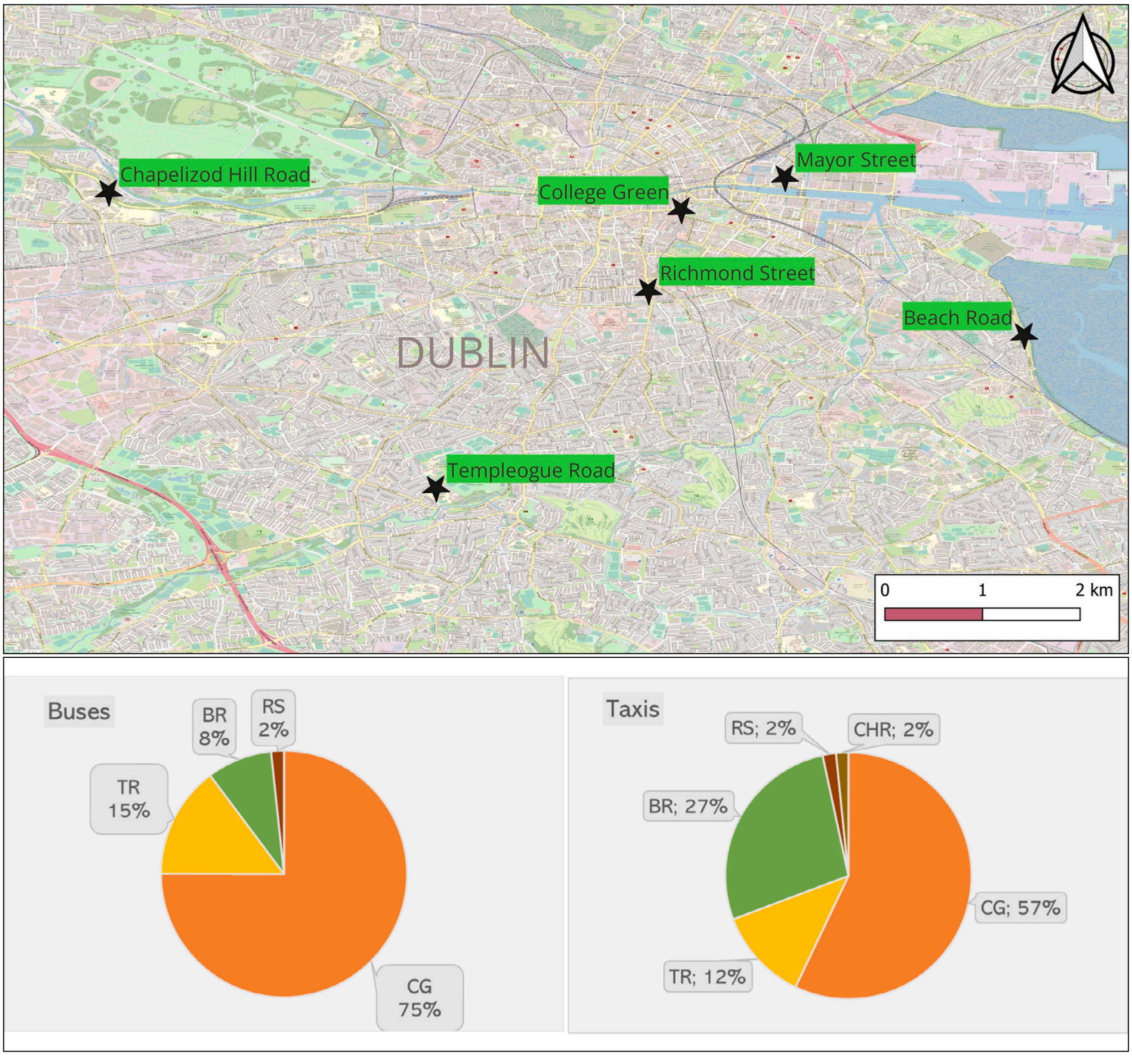

Fig. 1. Locations of remote sensing data collection sites (Map source: OpenStreetMap). The share of the data collected (in %) for buses and taxis at different sites is shown in the pie chart. Abbreviations: Beach Road (BR), Richmond Street (RS), Chapelizod Hill Road (CHR), College Green (CG), and Templeogue Road (TR).

Table 1
Site characteristics.

Site Name	Site Location	Lat	Lon	Gradient (%)	Mean speed (km/h)		Total no. of tests	
					Taxis	Buses	Taxis	Buses
CG	College Green	53.34438	−6.25972	1.0	22.4	19.0	4317	3430
TR	Templeogue Road	53.30164	−6.29739	0.2	34.1	33.2	921	673
BR	Beach Road	53.32509	−6.20702	0	27.4	23.4	2069	391
RS	Richmond Street	53.33194	−6.26476	0.8	25.2	19.6	133	77
CHR	Chapelizod Hill Road	53.34708	−6.34769	5.2	35	NA	122	NA

Note: Mayor Street was initially considered for data collection, but later omitted due to relatively low volume of traffic. NA represents not available.

2.2. Data collection and processing

Data were gathered during two distinct seasons: winter and summer. The winter campaign spanned from November 8th, 2021, to February 10th, 2022, while the summer campaign took place between May 4th, 2022, and June 30th, 2022. Weekdays were designated for data collection, excluding days characterised by heavy rainfall. At 8 am on typical days in both summer and winter, the instrument was set up at one of the sites. Data collection persisted until sunset during winter and till 5 pm during summer, facilitating the capture of the vehicle's rearview image for acquiring vehicle registration data. Prior to conducting the tests and once more in the afternoon, the instrument underwent calibration using gas cylinders with known concentrations obtained from BOC Limited, United Kingdom (Mahesh et al., 2023). Also, preliminary emission results in Dublin were compared with previous findings from cities in the United Kingdom with similar vehicle fleets, further strengthening confidence in the reliability and accuracy of the collected data (Grange et al., 2019; Carslaw et al., 2019b). The instrument was also routinely inspected, cleaned, and maintained at the end of every data collection day in accordance with the instructions provided by the manufacturer.

A camera captured photographs of the vehicle number plates that were used to obtain the vehicle registration numbers and, in turn, the vehicle type, make, model, mileage, engine size, fuel type, and year of registration. For vehicles registered in Ireland, the National Vehicle and

Table 2
Number of tests on buses and taxis by Euro standard and season.

Season \ Euro standard	Buses			Taxis						
	5	6	Total	4	5	6b	6c	6d (t)	6d	Total
Winter	282	1956	2243	284	1962	1325	263	179	44	4078
Summer	204	2112	2330	281	1837	1052	179	119	-	3482

Driver File (NVDF) was used to obtain the information. For those registered in the United Kingdom (UK), data was obtained from the UK Driver and Vehicle Licensing Agency (DVLA) and the Society of Motor Manufacturers (SMMT) Motor Vehicle Registration Information System (MVRIS). Euro standards of the vehicles were not recorded in these tests, and these were estimated using the registration year. Taxis complying with Euro 6 were further divided into Euro 6b, 6c, 6d-temp (t), and 6d. The mileage information in NVDF are populated from the compulsory National Car Test (NCT, 2023) which is a mandatory vehicle inspection programme in Ireland aimed at improving road safety and reducing vehicle emissions. Vehicles less than three years old are exempted, while vehicles between 4-9 years old are required to undergo the test every two years. Vehicles older than 10 years require an annual test.

In total, 136405 emission tests were conducted over the two campaigns. The vehicle types tested were private cars, buses, taxis, and vans, however this study focused on the emissions from buses and taxis and excluded private cars and vans. A total of 4573 tests were conducted for buses, with 2243 in winter and 2330 in summer. The number of tests conducted by the Euro standard for buses and taxis is shown in Table 2. For taxis, 4078 and 3482 tests are conducted in winter and summer, respectively, making it a total of 7575 tests. A few tests were omitted based on the validity of all gas measurements, calibration, audit status, and speed acceleration validity. The tests where the vehicle registration number could not be found were also removed from the analysis. Vehicles other than diesel vehicles were omitted for both buses and taxis. Further, only tests that provided valid NO_x measurements were considered. For the analysis, 1852 and 3207 valid tests were considered for buses and taxis, respectively. A significant proportion of the tests were conducted on the latest emission standard vehicles, Euro 6 in the case of buses and Euro 6c, 6d(t), and 6d in the case of taxis. In view of the space restrictions, the reader is referred to Mahesh et al. (2023) for further details regarding the data collection procedure.

The measured instantaneous vehicle speed, acceleration, and gradient at the site were used to calculate the vehicle specific power (VSP), which is the instantaneous power demand of the vehicle and expressed in kW/(metric) tonne. Figures S1 and S2 in Supplementary Information show the distribution of VSP of buses and taxis at different locations. As expected, for buses, the VSP is predominantly below 12 kW/tonne due to their low speeds in urban areas, with similar profiles for Beach Road and Templeogue Road. In the case of College Green, the VSP is further confined to values below 10 kW/tonne. However, for taxis, the VSP distribution has a much wider range (ranging up to 22 kW/tonne) due to relatively higher speeds.

2.3. Data analysis

The remote sensing methodology assumes that the dilution of CO_2 and pollutant emissions remains constant as the exhaust plume disperses, and all pollutant concentrations are reported relative to the CO_2 concentration. The fuel combustion process can be used to convert the pollutant concentration values to fuel-specific emission factors (EFs) in g/kg of fuel (Bernard et al., 2018). In the combustion process, carbon monoxide, other hydrocarbons, and oxides of nitrogen are emitted alongside carbon dioxide. Bernard et al. (2018) considers the molar mass of different pollutants to convert pollutant concentrations obtained to fuel-specific emission factors (in g/kg of fuel) based on the

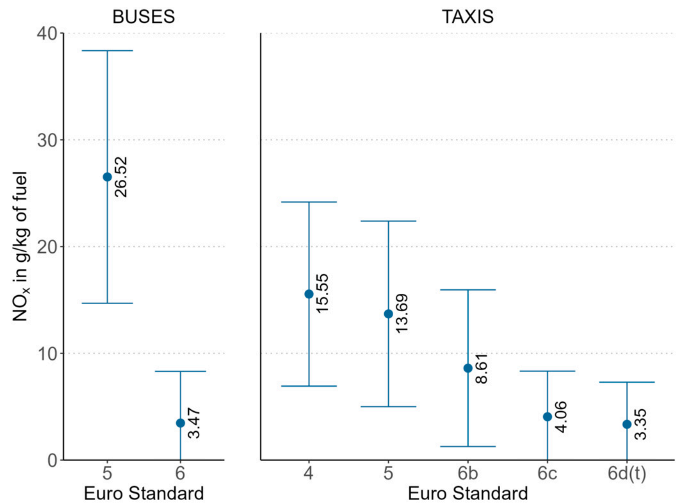

Fig. 2. Error bar plot for emissions by Euro standard for buses and taxis. Error bars are truncated at zero.

fuel type of the vehicle which is obtained from vehicle registration data (Equation (1)).

$$\text{Pollutant (in g/kg of fuel)} = \frac{M_{Pollutant}(g/mol)\times Pollutant(\%)/CO_2(\%)}{1+CO(\%)/CO_2(\%)+6\times HC(\%)/CO_2(\%)} \times \frac{1000}{MC(g/mol)+M_r\times MH(g/mol)} \quad (1)$$

Where, Pollutant(%)/CO_2 (%) is the pollutant concentration relative to CO_2; $M_{Pollutant}$ is the molar mass of the studied pollutant; MC is the molar mass of carbon equal to 12 g/mol; MH is the molar mass of hydrogen equal to 1 g/mol; M_r is the average molecular ratio of carbon and hydrogen representing the fuel composition with values of 1.92 and 1.87 for diesel and petrol, respectively.

3. Results and discussion

3.1. Effect of Euro class on EF

In this section, the effect of the emission standard of the vehicle on fuel-specific EFs (in g/kg fuel) is examined. Fig. 2 shows the trends in emissions of NO_x with respect to Euro standards for buses and taxis. The highest number of observations are for Euro 6 buses (1619) and Euro 5 taxis (1606). Regarding the trends in EF values, a significant reduction is seen in the average value for Euro 6 buses (3.47 g/kg fuel) compared to Euro 5 (26.52 g/kg fuel) ones. In the case of taxis, the emissions are presented for five different Euro standards, ranging from Euro 4 to Euro 6d(t). A decreasing trend is seen from Euro 4 to Euro 6d(t) with Euro 6d(t) having the lowest average EF value (3.35 g/kg fuel). A significant decrease in the average emissions is observed from Euro 5 to Euro 6b (37.1%) and also from Euro 6b to Euro 6c (52.8%).

Comparison of the trends observed with previous studies provides useful insights. The trends in the NO_x emissions for taxis in this study are similar to the findings reported in previous studies on passenger cars (Huang et al., 2020; Smit et al., 2021; Mahesh et al., 2023) that show a significant impact of stringent Euro standards on improvement

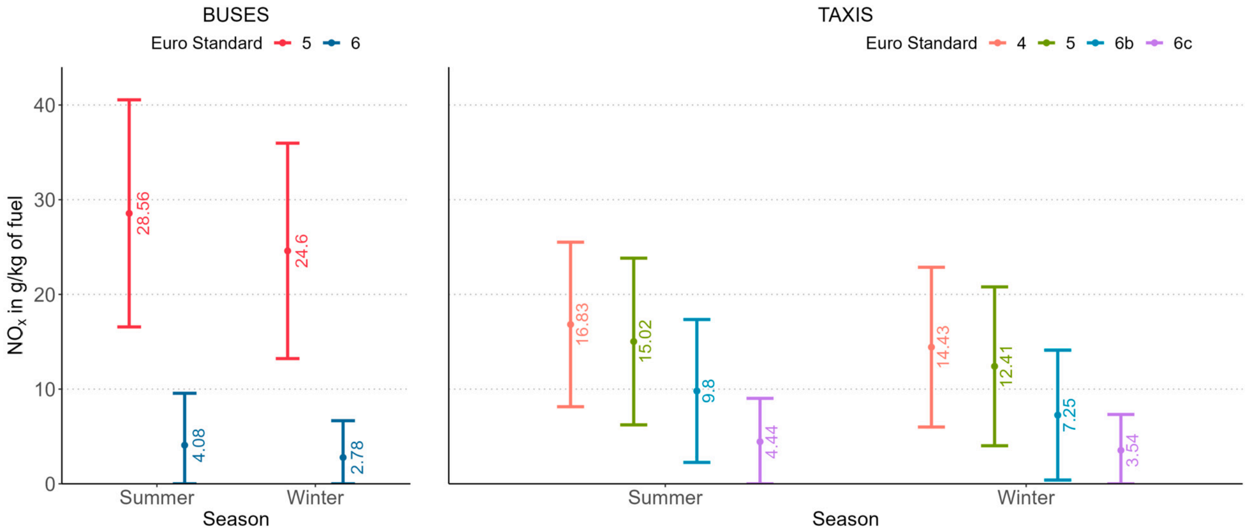

Fig. 3. Error bar plot for emissions by Euro standard and campaign for buses and taxis. Error bars are truncated at zero.

in emission performance. However, discrepancies between the trends in the emissions of taxis and passenger cars have also been reported. For instance, based on studies in Edinburgh and Glasgow, Lee and Bernard (2023) compared the NO_x emissions from taxis with private passenger cars and reported that emissions from diesel Euro 4 to Euro 6 taxis were 42%-68% higher compared to the private passenger cars.

There are few recent studies that have investigated the trends in the real-world NO_x emissions from in-use buses using remote sensing, thus limiting the scope for comparison. Bakhshmand et al. (2022) reported that the NO_x emissions consistently decreased across the buses measured in six European cities with increasing stringency of Euro emission standards. The study considered both city buses and coach buses and found that emissions from city buses were four times higher than coach buses. The authors mention that the high NO_x emissions could be due to the low load cycles and cold starts in the case of city buses. In an earlier study on buses, Carslaw and Rhys-Tyler (2013a) examined the NO_2 emissions from road vehicles in London, United Kingdom and found that OEM Selective Catalytic Reduction (SCR) fitted buses did not show reduced NO_x emissions during urban driving. Within the scope of the present study, we did not have access to data regarding the specific NO_x emission control system implemented. Therefore, we cannot definitively attribute the noted enhancements in EFs to the particular type or effectiveness of the emission control system present in the bus.

3.2. Effect of season and ambient temperature on emissions

In addition to the emission standard, the effect of season and ambient temperature on the variation of NO_x emissions is also of interest. The performance of the emission control systems in modern vehicles depends on the temperature of the exhaust gases (Reşitoglu et al., 2015). The main NO_x emission control systems in diesel vehicles are Exhaust Gas Recirculation (EGR), Lean NO_x Trap (LNT), and Selective Catalytic Reduction (SCR). Although, the engine temperature is not obtained from the remote sensing dataset, it is possible to analyze the effect of ambient temperature on the emissions of NO_x.

Fig. 3 shows the trends in the emissions of NO_x with respect to Euro standards for buses and taxis divided between the two measurement campaigns (summer and winter). In this case, Euro 6d(t) taxis are omitted due to the low number of observations. Euro 5 taxis occupy a major share in both the summer and winter campaigns. Regarding the trends in EF values in summer, a large reduction is seen in the average value for Euro 6b (9.80 g/kg fuel) compared to Euro 5 (15.02 g/kg fuel) ones. A significant reduction is also observed in winter when Euro 6b (7.25 g/kg fuel) is compared to Euro 5 (12.41 g/kg fuel). The trends are similar for both summer and winter campaigns, however the average EF values in winter are lower compared to the ones in summer for the same Euro standard. Similar findings are seen for buses as well when comparing summer and winter values.

The effect of ambient temperature on NO_x EFs for taxis is shown in Fig. 4. The analysis was restricted to taxis of two Euro standards (Euro 5 and 6b) due to the limited number of observations for other categories (Euro 4, 6c, and 6d(t)). The ambient temperature was divided into four categories, namely, 5-10 °C, 10-15 °C, 15-20 °C, and 20-25 °C, based on the range of ambient temperature observed during the data collection. In general, an increasing trend in the EFs is seen for both Euro 5 and Euro 6b taxis with an increase in the temperature with the highest value for the temperature range between 20-25 °C. The lowest values (12.14 g/kg fuel and 6.44 g/kg fuel) are in the temperature ranges 5-10 °C and 10-15 °C for Euro 5 and Euro 6b, respectively. In the case of buses (Fig. 4), the lowest EF value (2.1 g/kg fuel) is seen for Euro 6 standard buses with the temperature ranging between 10-15 °C with higher values (at least 30% increase) for temperatures above 15 and below 10 °C. In the case of Euro 5 buses, the EF value is 21% higher for the temperature range of 15-20 °C relative to the range of 10-15 °C with further increase at temperatures beyond 20 °C. The lowest value (22.8 g/kg fuel) is seen for the temperature ranging between 10-15 °C.

Three previous studies used remote sensing data to investigate the relationship between ambient temperature and NO_x emissions from diesel vehicles. Sjödin et al. (2018) investigated the effect of ambient temperature on NO_x emissions from Euro 5 diesel passenger cars using data from Stockholm, London, Rome, Madrid, and Athens. The temperature range considered was from just above zero to 35 °C. The NO_x emissions were minimum in the temperature range of 20-25 °C and increased on either side of this range. Grange et al. (2019) examined the effect of ambient temperature on NO_x emissions from diesel passenger cars and vans using data from ten regions in the United Kingdom. The authors found that Euro 6 diesel cars and vans showed a weaker temperature dependence and attributed it to the use of LNT and SCR systems in Euro 6 diesel vehicles. The range of the NO_x EFs reported was between 17.5-7.5 g/kg fuel for pre-Euro 6 cars and between 11.5-2.5 g/kg fuel for Euro 6 cars and the temperature ranged between 0 and 25 °C. Chen et al. (2020) evaluated the effect of ambient temperature on NO_x emission from LCVs and reported that lower temperatures were associated with higher NO_x emissions for Euro 3 to 5 diesel LCVs. The range of temperature was between 0 to 25 °C. Also, within Euro 5 and 6, the trend was almost horizontal for temperatures above 10 °C. The results

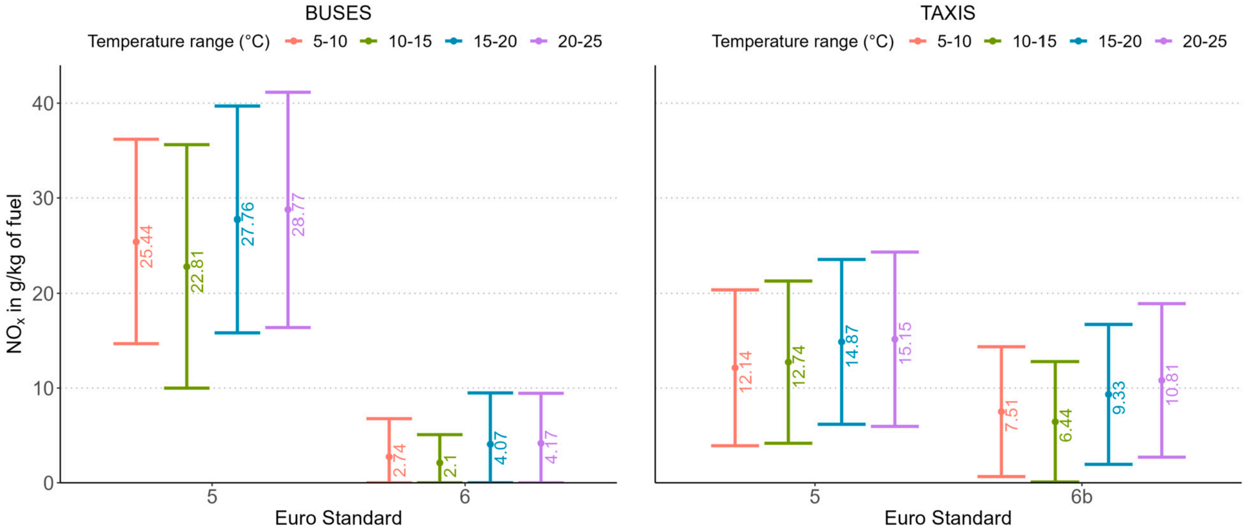

Fig. 4. Error bar plot for emissions by Euro standard and ambient temperature (°C) for buses and taxis. Error bars are truncated at zero.

in this paper for taxis are similar to these findings for passenger cars and vans in the UK and other European cities.

In conclusion, based on the ambient temperature range observed during this study, the trends in the emissions of NO_x exhibit similarities between the summer and winter seasons. Notably, the buses compliant with Euro 6 standards and the taxis compliant with Euro 6b standards demonstrate marginally lower emissions during the winter season in comparison to summer. Furthermore, this finding holds true even when conducting a detailed analysis across various ambient temperature ranges. Consequently, these results confirm that the ambient temperature does not significantly impact NO_x emissions in new vehicles such as the Euro 6 buses and Euro 6b taxis for the temperature ranging between 5-25 °C. This could be attributed to the satisfactory performance of advanced emission control technologies (such as LNT and SCR) which vehicle manufacturers have adopted in the newer vehicles to comply with Euro 6 standards. In this context, a recent study by Liu et al. (2023) investigated the impact of ambient temperature on exhaust emissions by meta-analysis, considering low ambient temperatures (−18 to −7 °C) and warm conditions (20-30 °C). The study concluded that improvement in vehicle emission control technology has alleviated the impact of higher emissions during low temperatures. Moreover, from the fitted curves for NO_x EF with ambient temperature, within the range of 5-25 °C as observed in Dublin, the NO_x emissions do not vary significantly. This provides confirmation to the trends observed in Fig. 4 for buses and taxis.

3.3. Effect of mileage on emissions

Access to accurate mileage data is crucial for various analyses involving vehicles, yet it is often challenging to obtain such information. As a result, researchers have resorted to utilising vehicle age as a substitute for mileage. However, the limitations of using vehicle age as a proxy for vehicle usage have been extensively examined by Davison et al. (2022). The authors employed quantile regression to investigate the relationship between vehicle age and mileage and their findings clearly demonstrate the discernible mileage disparities between taxis and passenger cars. It was also highlighted that taxi fleets and other commercial vehicle fleets have a distinct mileage-age relationship which may not be accurately modelled using simple linear regression.

In order to investigate the impact of mileage, the average NO_x emissions were computed for distinct mileage ranges based on the type of vehicle. Fig. 5 shows the effect of mileage on NO_x emissions from Euro 5 and Euro 6b taxis and from Euro 6 buses. The mileage of the taxis is categorised into ranges of 25000 km with a maximum value of 250000 km. This ensures the presence of a sufficient number of observations in each category for both Euro standards. However, in the case of Euro 6b, EF values for some mileage categories (0-25k and 225-250k) were omitted due to the insufficient number of observations (fewer than 30). The results show no clear trends in the average EF values over the entire range of mileage for both Euro 5 and Euro 6b standard taxis. This is consistent with the findings reported by Davison et al. (2022) for Euro 6 diesel passenger cars in the United Kingdom. The range of the average EF values for Euro 5 taxis is between 10.64 and 14.57 g/kg fuel. Moreover, it is interesting to note that taxis having lower mileage (<50000 km) show a relatively high average EF value, and also the taxis with high mileage (>200000 km) do not show a significantly high EF value.

The mileage range considered for buses was from 100000 km to 375000 km with only one category (Euro 6). The average EF value does not show a consistent increasing or decreasing trend. The lowest value of EF (2.03 g/kg fuel) is observed for the mileage range of 325k-350k km and the highest (4.02 g/kg fuel) for the mileage range of 125k-150k km.

Few studies have reported the effect of mileage on emissions from in-use vehicles. Carslaw et al. (2019b) evaluated the effect of mileage on NO_2 emissions from diesel passenger cars and reported that the emissions decrease with increasing vehicle mileage. The authors also reported a decreasing trend for all Euro standard vehicles (ranging from 3-6) and mileage up to 500000 km for Euro 3, 4, and 5 and 200000 km for Euro 6. Further, Carslaw et al. (2019a) analysed the durability of emission control systems of passenger cars in Europe based on emissions of NO_x, CO, and HC. The study found that emissions of NO_x from Euro 5 and 6 diesel cars do not change with an increase in vehicle mileage. The findings in this study for taxis are consistent with those of passenger cars in Europe and likely due to the continued optimum performance of the exhaust after-treatment technologies.

It is important to note here that few recent studies have examined the durability of vehicle emission control systems under real driving conditions (Hao et al., 2022). Based on the RDE testing of two heavy-duty diesel trucks in China at intervals of 30000 km, Hao et al. (2022) report that NO_x emissions increase with vehicle mileage for mileage up to 200000 km. Similar studies on the latest light-duty diesel vehicles would be useful for comparison with RS measurements. The consistent reduction in the NO_x EF for Euro 6b taxis beyond 150000 km (Fig. 5) could be perhaps due to other disaggregate factors such as periodic vehicle maintenance and impact of different vehicle models. A long term RS database of vehicle emissions would enable further examination of the impact of mileage on emissions at an individual vehicle level.

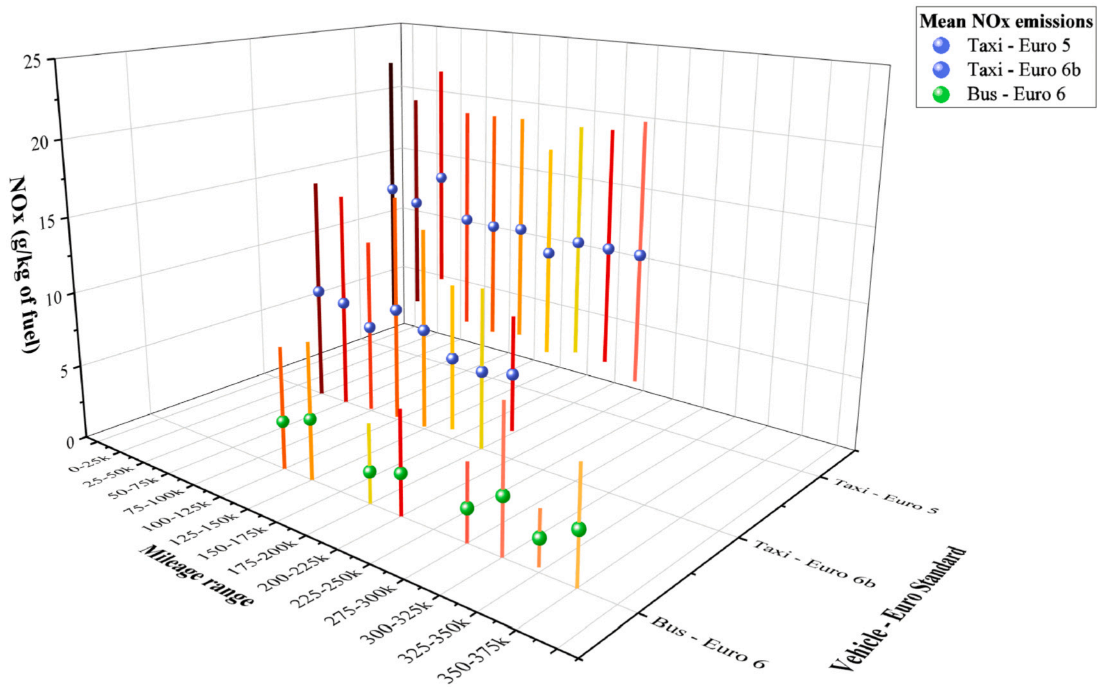

Fig. 5. Error bar plot for emissions by Euro standard and mileage for taxis and buses. The colour of the error bars represents different mileage ranges. Error bars are truncated at zero. (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

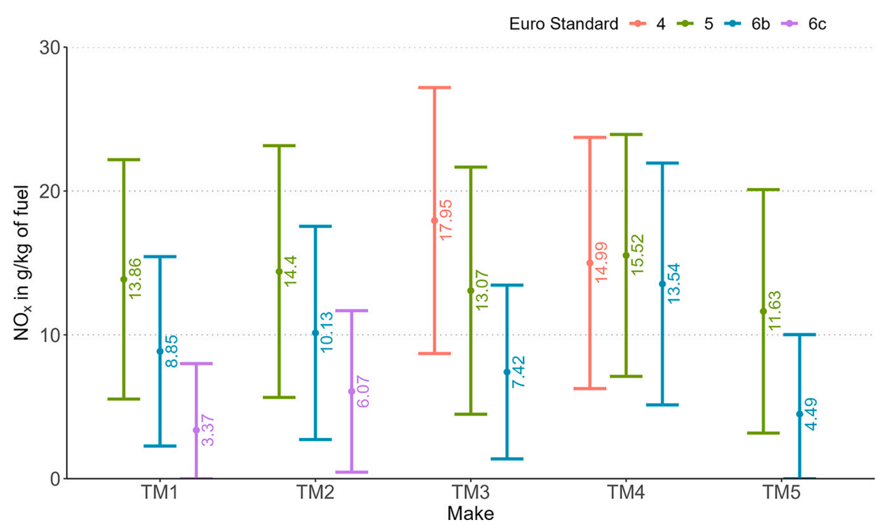

Fig. 6. Error bar plot for emissions by Euro standard and make for taxis. TM1 to TM5 represent the most common makes of taxis. Error bars are truncated at zero.

3.4. *Effect of make on emissions*

The emission control system employed in a vehicle is contingent upon its manufacturer. Various emission control systems in vehicles exhibit distinct performance characteristics, and comprehending these disparities can be beneficial in assessing the fleet for vehicles with high emissions. For example, Grange et al. (2019) reported that LNTs were less effective than SCR at reducing NO_x from vehicles. In this analysis, the makes of the taxis and buses are anonymized due to privacy concerns. Fig. 6 presents the trends in emissions of NO_x for the top five makes of taxis (represented as TM1, TM2, TM3, TM4, and TM5) for four Euro standards in Dublin. These top five makes for taxis were also the makes with the highest shares in the Irish taxi fleet as mentioned in CSO (2019). On excluding taxis of makes which have less than 30 observations, it is to be noted that the Euro 6c category is shown only for those of make TM1 and TM2. A decreasing trend in the average EF is observed in the case of taxis of makes TM1, TM2, TM3, and TM5 with higher emission standards. In the case of TM4 taxis, the average EF value only differed slightly for Euro 4, 5 and 6b categories, unlike other vehicle makes, and we did not have sufficient observations of Euro 6c taxis. Among the five manufacturers, average NO_x emissions from Euro 6c compliant taxis of make TM1 were the lowest and Euro 4 compliant TM3 taxis were the highest. The results are limited by the sample sizes in each category to conclude a statistically significant difference. In addition, the effect of mileage and engine size was not explicitly considered. Further, it is important to note here that within the same vehicle make, there could be models having different emission control systems which is not considered here. The results on buses are not shown in the figure due to the smaller sample sizes for different combinations of Euro standards, and the makes.

Distinct patterns in the NO_x EFs for different vehicle makes, as found in this study, has also been reported in previous studies for passenger cars, buses, and LCVs. Borken-Kleefeld et al. (2018) found that cars of Renault and Fiat were the highest in NO_x emissions in Euro 5 and

Euro 6 category. Toyota and BMW make cars were among the lowest NO_x emitters. Dallmann et al. (2018) examined the NO_x emissions from buses of three different makes (Alexander Dennis, Volvo, and Wrightbus) in London and found the emissions from Wright bus to be 3-4 times higher than Alexander Dennis. Further, Chen et al. (2020) examined the emissions from LCVs in Europe and reported that some manufacturers perform better than others. For instance, Nissan-Renault had higher NO_x emission for Euro 5 and Euro 6a,b in the N1-I category. Volkswagen had the lowest absolute emissions for Euro 6a,b in class N1-II. Chen et al. (2020) mention that manufacturers employ different in-use emission control strategies with some being more stringent than others. This could also be the reason for the distinct patterns observed in this study for Euro 4, 5, 6b and 6c compliant taxis. Further analysis based on the specific emission control systems present in different vehicle makes would provide more insights, however, this is beyond the scope of this study.

3.5. Policy implications

The findings presented in this paper have significant implications for policies aimed at controlling NO_x emissions from buses and taxis in urban areas. Firstly, compelling evidence supports the implementation of an early phase-out of Euro 5 buses and taxis compliant with Euro 5 or lower standards. Further, Euro 6b taxis exhibits more than double the NO_x emissions compared to Euro 6c taxis, underscoring the importance of planning for the phasing out of Euro 6b compliant taxis. Currently, there exists a 10-year age limit for taxis in Dublin, but taxi drivers have been granted an extension because of a global shortage of new cars. In Edinburgh, the minimum standard for taxis and private hires was Euro 5, whereas in Glasgow, a 7-year age limit exists for private hires (Lee and Bernard, 2023). Strategies to encourage newer vehicles and restrict older emission standard vehicles, at least within the city centre, need to be implemented in Dublin and possibly in other cities in Ireland. These findings may have a significant impact on the achievement of emission reduction goals. For instance, Ireland has committed to reducing NO_x emissions by 69% by 2030 compared to the emission levels in 2005 (EPA, 2023).

The number of buses in Ireland has reduced significantly in the last decade (National Transport Authority (NTA), 2021a). Further, according to the Bus and Rail Statistics report, the Dublin bus fleet consists of about 1000 buses with an average age of 6.9 years. From the collected data, 47% are less than five years old and 17% are less than two years old. Also, the average age of the bus is 5.2 years which is slightly lower than the average age (6.9 years) of the entire fleet of Dublin bus. Moreover, the number of unique buses in the dataset is 751 which includes more than 70% share of the Dublin bus fleet. Thus, the bus fleet in Dublin is relatively new and significantly less emitting.

The predominantly diesel powered taxi fleet of Dublin (10687 out of 21326 taxis in Ireland including hackneys and limousines based on 2019 data) requires more attention and regulation to reduce their emissions. In 2019, the average age of taxis in Ireland was 6.3 years (CSO, 2019). Based on the 2020 data, only about 40% of the taxis in Ireland are less than six years old (National Transport Authority (NTA), 2021b). Due to the impact of the pandemic and other factors, the number of taxis in Ireland reduced from 21326 in 2019 (CSO, 2019) to 19352 in 2020 (National Transport Authority (NTA), 2021b). In fact, the number of taxis has been steadily decreasing from more than 23000 in 2011 to less than 19500 in 2020 (National Transport Authority (NTA), 2021b). On a positive note, the government has introduced the electric vehicle taxi scheme which provides a grant of up to €25000 for taxi drivers to buy plug-in hybrid or battery electric vehicles (DoT, 2022).

This paper also investigated the effect of season, mileage, and make on NO_x emissions. First of all, regarding the effect of season on emissions, the analysis in this paper reveals no significant differences in trends and average EF values between summer and winter. Secondly, mileage alone may not accurately reflect the emission performance of buses and taxis. Instances where high-mileage Euro 6 buses and Euro 5 taxis exhibit lower emissions than their low-mileage counterparts were observed. Hence, while mileage is an important parameter for screening the vehicle fleet for high-emitters, excluding low-mileage vehicles may introduce bias into the screening process. Finally, it is crucial to identify the dominant vehicle makes in the bus and taxi fleets, as different makes may employ varying NO_x emission control systems. Consequently, certain makes may have a higher probability of being high-emitters compared to other relatively cleaner makes.

4. Conclusions

This study presents an analysis of NO_x emissions from in-use buses and taxis in Dublin, Ireland using on-road remote sensing measurements. Several factors affecting the emissions such as Euro standard, season, ambient temperature, mileage, and make of the vehicle were considered. Notably, the vehicle emission measurements included a significant number of the latest Euro 6 compliant buses and taxis of different makes, and the mileage data of a large percentage of these vehicles. This allowed greater insights to be drawn regarding the impact of these factors on the emissions from buses and taxis which has not been adequately examined in prior remote sensing-based studies. The results show that NO_x emissions from Euro 6b taxis and Euro 6 buses are significantly low in comparison to the previous emission standard vehicles. In particular, the average emissions from taxis reduce by 37% from Euro 5 to Euro 6b and average emissions from Euro 6 buses are significantly lower (−87%) compared to Euro 5. For diesel taxis, the NO_x emissions varied slightly for different makes. Furthermore, no clear increasing or decreasing trends in the average EF values were seen with mileage for both Euro 5 and Euro 6b compliant taxis. In summary, the bus fleet in Dublin is relatively new and significantly less emitting. However, the predominantly diesel powered taxi fleet requires more attention and regulation to curtail their emissions. The results of this study have important implications for managing air quality in urban areas where buses and taxis collectively contribute substantially to overall emissions.

This study has some limitations that indicate potential avenues for future research. To deepen our understanding and validate the findings, a more extensive dataset would be advantageous. Deploying RS systems for longer duration (one year or more) across multiple locations in Dublin and other Irish cities would provide researchers with a comprehensive dataset, enabling the acquisition of robust findings regarding emission trends in the vehicle fleet. The range of VSP considered in this study was limited to urban driving (Figures S1 and S2 in Supplementary Information) and do not cover idling and high speed conditions. An extensive study with the full spectrum of VSP values can represent the average EFs throughout the entire driving cycle of a vehicle.

CRediT authorship contribution statement

Mounisai Siddartha Middela: Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Srinath Mahesh:** Conceptualization, Data curation, Investigation, Methodology, Project administration, Writing – original draft. **Aonghus McNabola:** Funding acquisition, Project administration, Resources, Writing – review & editing. **William Smith:** Funding acquisition, Project administration, Resources, Writing – review & editing. **David Timoney:** Funding acquisition, Project administration, Resources, Writing – review & editing. **Ali Ekhtiari:** Investigation, Writing – review & editing. **Ben Fowler:** Funding acquisition, Project administration, Resources, Writing – review & editing. **Paul Willis:** Funding acquisition, Project administration, Resources, Writing – review & editing. **Rebecca Rose:** Funding acquisition, Project administration, Resources, Writing – review & editing. **Jasmine Wareham:** Funding acquisition, Project administration, Resources, Writing – review & editing. **Hannah**

Walker: Funding acquisition, Project administration, Resources, Writing – review & editing. **Bidisha Ghosh:** Funding acquisition, Project administration, Resources, Writing – review & editing.

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.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary material

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