

# Real-world assessment of vehicle air pollutant emissions subset by vehicle type, fuel and EURO class

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1 Real-world assessment of vehicle air pollutant emissions subset by vehicle type,  
2 fuel and EURO class: new findings from the recent UK EDAR field campaigns, and  
3 implications for emissions restricted zones

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7 **Abstract.**

8 This paper reports upon and analyses vehicle emissions measured by the Emissions Detecting and  
9 Reporting (EDAR) system, a Vehicle Emissions Remote Sensing System (VERSS) type device, used in  
10 five UK based field campaigns in 2016 and 2017. In total 94940 measurements were made of 75622  
11 individual vehicles during the five campaigns. The measurements are subset into vehicle type (bus,  
12 car, HGV, minibus, motorcycle, other, plant, taxi, van, and unknown), fuel type for car (petrol and  
13 diesel), and EURO class, and particulate matter (PM), nitric oxide (NO) and nitrogen dioxide (NO<sub>2</sub>) are  
14 reported. In terms of recent EURO class emission trends, NO and NO<sub>x</sub> emissions decrease from EURO  
15 5 to EURO 6 for nearly all vehicle categories. Interestingly, taxis show a marked increase in NO<sub>2</sub>  
16 emissions from EURO 5 to EURO 6. Perhaps most concerningly is a marked increase in PM emissions  
17 from EURO 5 to EURO 6 for HGVs. Another noteworthy observation was that vans, buses and HGVs of  
18 unknown EURO class were often the dirtiest vehicles in their classes, suggesting that where counts of  
19 such vehicles are high, they will likely make a significant contribution to local emissions. Using Vehicle  
20 Specific Power (VSP) weighting we provide an indication of the magnitude of the on-site VERSS bias  
21 and also a closer estimate of the regulatory test/on-road emissions differences. Finally, a new 'EURO  
22 Updating Potential' (EUP) factor is introduced, to assess the effect of a range of air pollutant  
23 emissions restricted zones either currently in use or marked for future introduction. In particular, the

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24 effects of the London based Low Emission Zone (LEZ) and Ultra-Low Emissions Zone (ULEZ), and the  
25 proposed Birmingham based Clean Air Zone (CAZ) are estimated. With the current vehicle fleet, the  
26 impacts of the ULEZ and CAZ will be far more significant than the LEZ, which was introduced in 2008.

27 **Keywords.** EDAR; VERRS; Real-world driving; Vehicular emission factors; EURO standards; Urban areas;  
28 Air Pollution; Nitrogen oxides, Particulate matter

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## 29 1. Introduction

30 Air pollution is of great and current concern worldwide. It is the leading environmental risk  
31 factor for global human health. It is estimated to be responsible for 4.2 million premature  
32 deaths worldwide (1). In the UK alone, the Committee on the Medical Effects of Air Pollution  
33 (COMEAP) estimates that approximately 40,000 premature deaths are caused annually by air  
34 pollution (2). A wide body of research has evidenced the effects of air pollution upon physical  
35 health; it causes both mortality and multiple morbidities including respiratory and  
36 cardiovascular illness (3, 4). More recently links between cognition, mental health and  
37 dementia and air pollution have been identified (5-7).

38 Typically, the most important air pollutants from a health perspective are particulate matter  
39 (PM) and nitrogen dioxide (NO<sub>2</sub>). Vehicle exhaust emissions are the major source of urban  
40 NO<sub>2</sub> and a significant source of PM. Hence real-world vehicular emissions of these pollutants  
41 are vitally important to be able to understand and hence reduce air pollutant concentrations.  
42 Since NO<sub>2</sub> rapidly interconverts between nitric oxide (NO) under typical photochemical  
43 conditions in the urban atmosphere, it is also important to measure the vehicular emissions  
44 of NO in addition to NO<sub>2</sub>. From a climate perspective, it is also important to monitor vehicular  
45 emissions of carbon dioxide (CO<sub>2</sub>).

46 Government agencies need to generate action plans to reduce the adverse impact of vehicles  
47 on human health and environmental degradation. This is especially essential in the urban  
48 areas where vehicle numbers are highest. These action plans are usually divided into two  
49 sub-categories: (1) vehicle emissions reduction through regulation, and (2) local emission  
50 reduction actions and interventions.

51 In the first sub-category, various countries and legislative regions have prepared limit values  
52 to restrict vehicular emissions. For instance, the European Union and European Economic  
53 Area (EEA) member states introduced European emission standards, which define the  
54 acceptable limits for exhaust emissions of new vehicles produced and sold in that area. To-  
55 date, the EURO standards have been updated six-times, in which EURO 6 and EURO VI are  
56 the most recent for light and heavy-duty vehicles, respectively. Vehicle emission factors have  
57 been shown to be significantly affected by real-world driving conditions such as - driver  
58 behaviour, fuel quality, vehicle mileage, weather conditions, and many other factors. The role  
59 of cold starts has also shown to affect vehicle emissions (8).

60 In the second sub-category, local actions are implemented to reduce or restrict vehicle  
61 activities in the most polluted areas or encourage the use of alternative vehicle technologies.  
62 The UK Low Emission Zones (LEZs), Ultra Low Emission Zones (ULEZs), and Clean Air Zones  
63 (CAZs), described and discussed in further in Section 4.2, are examples of major  
64 interventions. Other options to reduce urban pollution include public transport service  
65 expansions, alternative vehicle infrastructure development (e.g. electric vehicle charging  
66 points and alternative fuelling stations), and traffic flow management and calming activities  
67 (9). Previously, it has been shown that implementing the LEZ in London has had notable

68 impacts upon PM concentration, while the variation in the concentration of Nitrogen Oxides  
69 ( $\text{NO}_x$ ) seems to be insignificant (10, 11).

70 There are three main classes of vehicle emissions measurements methods. Firstly, vehicle  
71 testing under controlled laboratory conditions using chassis dynamometers (see for example  
72 (12)). The highly controlled driving conditions and restricted environmental conditions of the  
73 dynamometer tests make associated measurements highly reproducible, but limit their ability  
74 to be completely representable of real-world emissions. Secondly, Portable Emission  
75 Measurement Systems (PEMS) instruments installed at the tailpipe of the vehicles are used to  
76 measure the instrumented vehicle's on-road emissions. Although real-world measurement  
77 has been widely cited as an advantage over dynamometer methods, reported limitations  
78 include laborious installation procedures and the trade-off between safe and representative  
79 driving activity (13). In addition, there are some concerns on the adverse impact of PEMS  
80 weight on the measurement results (14). Finally, passing vehicle emissions using monitoring  
81 systems deployed at roadside or near road locations. The cost and maintenance of these  
82 instruments, and relatively brief 'per vehicle' measurements are acknowledged limitations,  
83 these approaches arguably provide the most comprehensive description of local fleet  
84 emissions (15).

85 A number of reports and studies have been published on the emission performance and  
86 emission characteristics of the vehicles with different EURO standards. For example, Kwon et  
87 al. studied the characteristics of six EURO 6 light-duty diesel vehicles using a PEMS (16). They  
88 observed that the status of the air condition system of the vehicle, on or off, as well as  
89 outdoor ambient temperature could significantly impact on  $\text{NO}_x$  emission factor of the  
90 studied vehicles. Chen et al. used chassis dynamometer to assess the role of several factors

91 on the emission of one EURO VI diesel city bus (17). Their results show that the emission  
92 factors are influenced to some extent by different factors, e.g. fuel type, driving behaviour  
93 and road conditions. Lujan et al. used PEMS to study the emission performance of a EURO 6  
94 light-duty diesel vehicles under different speeds (18). Results show that acceleration at low  
95 speeds leads to higher NO<sub>x</sub> emissions compare to a similar action at high speeds. Simonen et  
96 al. conducted different experiments in the laboratory and real-world conditions on three  
97 EURO 6 light-duty vehicles (19). Their results show notable differences between emissions  
98 under real-world and controlled conditions. The same was observed in the study of  
99 Triantafyllopoulos et al., when the CO<sub>2</sub> and NO<sub>x</sub> emissions of three EURO 6 diesel vehicles  
100 were investigated under the controlled and on-road conditions (20). Mere et al. also used  
101 PEMS to study the high instantaneous NO<sub>x</sub> emissions from Euro 6 diesel passenger cars (21).  
102 They investigated the operation of three SUV diesel passenger cars and found that high  
103 instantaneous NO<sub>x</sub> emission contributes a large amount of total NO<sub>x</sub> emission. Grigoratos et  
104 al. used PEMS to study the emission performance of five EURO VI heavy-duty vehicles under  
105 typical driving conditions (14). Results illustrated overall lower emissions compared to older  
106 technology heavy-duty vehicles.

107 However, much of published literature derives from dynamometer and PEMS studies which  
108 tend to be limited to small numbers of vehicles, and few provide a systematic comparison of  
109 multiple vehicle types and emissions classes. One noteworthy exception is the analysis of  
110 PEMS data from 149 EURO 5 and 6 diesel, gasoline and hybrid light-duty vehicle reported by  
111 O'Driscoll et al [21]. This study provides a robust estimate of the relative scales of NO<sub>x</sub>  
112 emissions form EURO 6 diesel and gasoline vehicles. However, a substantial number of real-  
113 world PEMS studies would be required to achieve a comprehensive understanding on the  
114 emission performance of vehicles of different EURO standards.

115 In recent years, Vehicle Emissions Remote Sensing Systems (VERSSs) have emerged as a  
116 technique that allows for measurement of a significant number of vehicles under on-road  
117 conditions. These systems come in various configurations, but in general they measure the  
118 absorption of light by the exhaust of passing vehicles. The extinction of light at certain  
119 wavelengths of light is attributed to the concentration of chemical species present in the  
120 exhaust plume.

121 Most VERSS employ an across-road open-path instrument design, with a light source that  
122 generates a light beam across a road lane at vehicle exhaust height (22). More recently,  
123 active (or high-volume) sampling methods have also been used to measure the emissions of  
124 passing vehicles. These systems were introduced to address limitations associated with the  
125 open-path across-road remote sensing systems (for further discussion see e.g. (12)). For  
126 example, using the absorption of light from a single beam projected across the monitored  
127 vehicle lane as the measured method, makes results highly sensitive to exhaust position and  
128 degree of exhaust plume/light beam intersection, a particular issue for heavy duty vehicle  
129 (HDV) data capture because of the wide range of exhaust positions. As a result, one of the  
130 earliest active sampling methods was On-road Heavy-duty Vehicle Emissions Monitoring  
131 System (OHMS) system developed by Bishop et al. for Heavy Duty Vehicles with higher cab-  
132 mounted exhausts (13). Unlike remote sensing, active sampling methods can be paired with  
133 non-optical measurement methods, which is a particular advantage for emissions like fine  
134 particulate that are not reliably measured using optical methods.

135 VERSSs have been employed in the UK street networks since almost two decades ago to drive  
136 a detailed picture of the on-road vehicle emissions. One of the earliest VERSS campaigns in  
137 UK has been conducted by the University of Leeds and Enviro Technology plc between 2007

138 and 2010 (23). The most interesting finding of that study was that NO emission in diesel  
139 passenger cars had not reduced as much as previously estimated. The first direct  
140 measurements of other nitrogen oxides in the UK using VERSS had been conducted by  
141 Carslaw et al (24). They observed little evidence of NO<sub>x</sub> emission reduction from all types of  
142 diesel vehicles. Another VERSS campaign had been conducted in two UK cities, i.e. York and  
143 London, in 2017 and early 2018 (25). Results show that NO<sub>2</sub> emissions tend to decrease with  
144 increasing vehicle mileage. Grang et al., conducted VERSS campaigns in 10 regions and 26  
145 sites throughout the UK in 2017 and 2018 (26). The main finding of their study was that NO<sub>x</sub>  
146 emission in passenger cars were found to be significantly dependent on ambient  
147 temperature.

148 In this paper we report on vehicular emissions measured by one of the infrared laser based  
149 VERSS, the Emissions Detection and Reporting (EDAR) system, which was developed and  
150 commercialized by Hager Environment and Atmospheric Technologies (HEAT). A schematic  
151 diagram of EDAR is provided in Figure 1. The EDAR has a number of unique features by  
152 comparison to conventional across-road VERSS, most notably: (1) The EDAR measures species  
153 using Differential Absorption LIDAR (DiAL), a technique which is widely reported to be more  
154 sensitive, selective and less susceptible to drift than the conventional absorption  
155 spectroscopy-based methods employed by other VERSSs (15, 27, 28). (2) EDAR measures NO<sub>2</sub>  
156 directly. Many other commercialised instruments, for example older RSDs, measured NO and  
157 estimated NO<sub>2</sub> and NO<sub>x</sub> by assuming fixed ratio contributions, a practice highlighted as  
158 potentially misleading (29). (3) Although, unlikely to be unambiguous, the approach could  
159 provide a better estimate of vehicle-based particulate matter (PM) emissions than  
160 conventional VERSSs because there are some early indications that it is more sensitive to  
161 finer PM than the conventional optical methods used by other VERSSs (See (28)). (4) All



162 VERSSs have an open-path configuration. However, unlike others that are deployed across-  
163 road, the EDAR is down-facing with (an eye-safe) laser light source and analyser mounted 5 m  
164 above the road and a reflector strip on the road to reflect light from the source back to  
165 analyser. This means the EDAR is much less sensitive to exhaust height than conventional  
166 across-road VERSS. The 'up high' deployment of the source/analyser unit also means the  
167 system should be less susceptible to system fouling, e.g. from road-level dirt resuspension  
168 and splash-back from passing vehicles. As the strip is placed on the road perpendicular to  
169 traffic flow and the EDAR scans back and forth along the strip, it generates a 3D image of the  
170 vehicle emission plume that is arguably a more representative measure of exhaust plumes  
171 than the single fixed-height beam used by across-road methods. The PM measurement is a  
172 relatively recent output from HEAT and the EDAR output in its current nanomole/mole  
173 format may hinder its use, so perhaps there is still work for be done to refine EDAR PM.  
174 However, earlier (admittedly limited) PEMS comparisons were encouraging and this novel  
175 data source is worth further investigation.

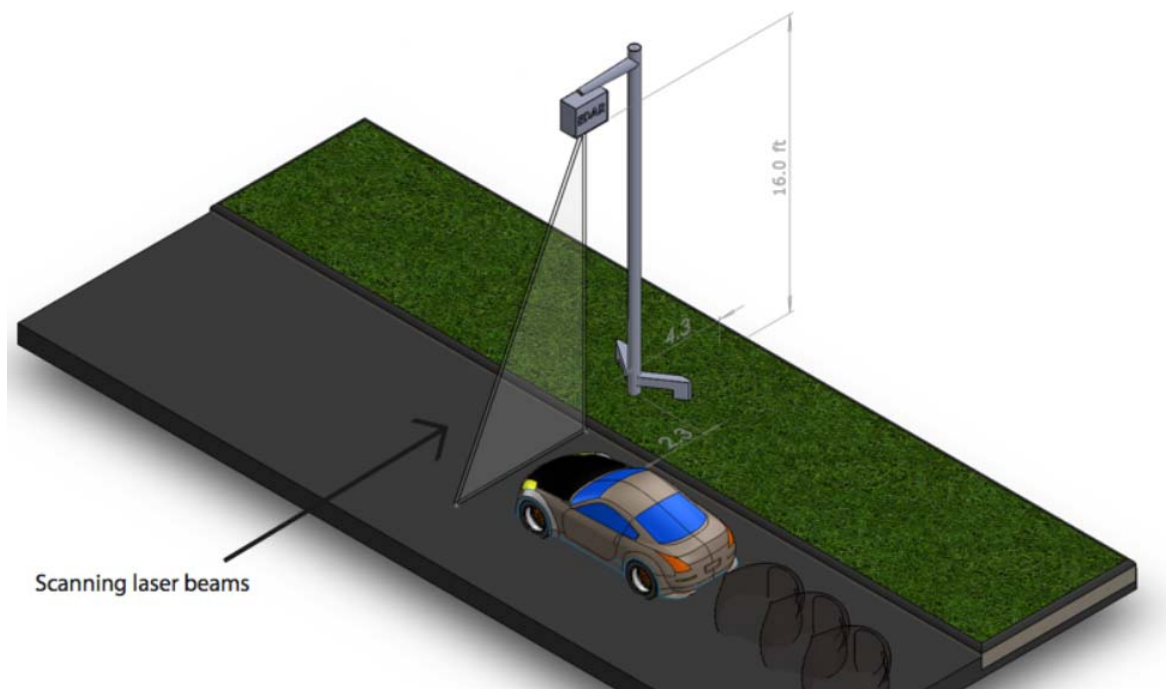


Figure 1. Schematic picture of HEAT EDAR (<https://www.heatremotesensing.com>).

176

177 Based on the discussions above, the main aim of the present study is to provide answers to  
 178 the following questions:

- 179 - How do emissions from different vehicle types vary?  
 180 - Within the same vehicle type, how do emissions vary with respect to fuel type and  
 181 EURO class?  
 182 - What is the likely quantitative impact of updating the fleet EURO standards based on  
 183 the different UK abatement strategies such as LEZ, ULEZ, and CAZ?

184 While across-road VERSS studies have already provided some information of these topics (23-  
 185 26, 29), data from an independent source and technique like EDAR expands the evidence  
 186 base and increases the confidence in consistent observations. EDAR also potentially provides  
 187 more comprehensive and direct comparison of fleet classes with very different exhaust

188 positions and configurations, e.g. motorcycles, cars, buses and HGVs. The results of this study  
189 can be used to inform policies aimed at improving air quality and reducing greenhouse gas  
190 emissions.

191

192

## 193 2. EDAR deployment in UK

194 The EDAR was first brought to the United Kingdom in 2016 and deployed at three sites,  
195 Tyburn in Birmingham, Marylebone Road in Central London and Blackheath in Greenwich, as  
196 part of work funded by the Department for Transport's (DfT) Local Transport Air Quality  
197 Challenge Innovation Grant October 2015. This was a small-scale study in which the EDAR  
198 was deployed alongside existing ambient air quality monitoring facilities at sites that were  
199 non-ideal for VERSSs in order to evaluate EDAR performance under challenging conditions  
200 and by comparison with two other real-world emissions measurement methods, Portable  
201 Emissions Measurement System (PEMS) and car chaser vehicle (SNIFFER) (28). The observed  
202 agreements between the results of EDAR and the other real-world emissions measurement  
203 methods demonstrated that EDAR could provide a reliable measure of vehicular emissions  
204 under the real-world conditions (28). The EDAR returned to the UK in March 2017 for three  
205 longer fleet-characterisation focused studies funded by the East Central Scotland Vehicle  
206 Emissions Partnership (ECSVEP), Transport Scotland (TS), West Lothian Council and North  
207 Lanarkshire Council. This study reports on the analysis of data collected during the first five  
208 EDAR deployments, namely Tyburn, Marylebone Road and Blackheath in 2016, and  
209 Edinburgh and Broxburn (2 of the 3 2017 deployments).

## 210 3. Materials & Methods

### 211 3-1. EDAR data

212 The data obtained from the EDAR system are passing vehicle emission measurements of CO<sub>2</sub>,  
213 NO, NO<sub>2</sub>, and PM, exhaust temperature, vehicle registrations captured by Automotive  
214 Number Plate Recognition (ANPR) system, collocated speed camera measurements of speed  
215 and acceleration, and simultaneous ambient information from a weather station unit. After  
216 the field campaigns were completed, the ANPR records were used to merge this and other  
217 vehicle specific data from vehicle fleet registration databases (Driver Vehicle Licensing  
218 Authority (DVLA) and Motor Vehicle Registration Information System (MVRIS) for 2016  
219 measurements and Society of Motor Manufacturers Traders (SMMT) for 2017  
220 measurements), and this was used to subset the vehicle emissions data according to vehicle  
221 type (bus, car, HGV, minibus, motorcycle, other, plant, taxi, van, and unknown), fuel type for  
222 car (petrol and diesel), and EURO class. For further information regarding the performances  
223 of the EDAR and ANPR, please see Ropkins et al. (28) and Sulaiman et al. (30), respectively.  
224 Although the measured fleets included a small number of alternatively fuelled vehicles, the  
225 numbers were not sufficient for statistically robust comparison and analysis is restricted to  
226 petrol and diesel vehicles.

### 227 3-2. Data analysis

228 EDAR data was converted from the pollutant/CO<sub>2</sub> ratio form provided by the EDAR  
229 manufacturer into the grams-per-kilometre (g/km) form and analysed using the following  
230 procedures. Gaseous species were converted to g/km using the following equation:

$$231 \quad [n]_{g/km} = ratio_{[n]/CO_2} \times [CO_2]_{g/km} \times mwt_{[n]/CO_2} \quad (1)$$

232 where n is the species (CO, NO, NO<sub>2</sub>),  $ratio_{[n]/CO_2}$  is the EDAR measurement,  $[CO_2]_{g/km}$  is  
 233 the CO<sub>2</sub> (g/km) emission rate derived from the available datasets, and  $mw_{[n]/CO_2}$  is the  
 234 molecular weight ratio of n to CO<sub>2</sub>. NO<sub>x</sub> emissions were calculated in line with the European  
 235 vehicle type approval definition of NO<sub>x</sub> (g/km) by the following equation:

$$236 \quad [NO_x]_{g/km} = [NO_2]_{g/km} + [NO]_{g/km} \times mw_{NO_2/NO} \quad (2)$$

237 where  $mw_{NO_2/NO}$  is the NO<sub>2</sub>/NO molecular weight ratio, i.e. approximately 46/30. PM was  
 238 reported by EDAR in nanomole/mole. As an alternative to reporting emissions in these molar  
 239 units, we used the PM comparison plot generated from data collected as part of the PEMS  
 240 drive-through EDAR evaluation exercise of the Birmingham and London EDAR study (28) as a  
 241 field calibration to convert the EDAR nanomole/mole outputs to gram of particulate per  
 242 kilogram CO<sub>2</sub> equivalents, before applying the above method to derive an estimate of PM  
 243 emissions in g/km units.

244 Statistical measures of emissions were calculated using a boot strapping approach based on  
 245 that previously used by Carslaw & Rhys-Tyler, (29). In boot strapping methods, the selected  
 246 sample, e.g. a subset of with common characteristics such as vehicle type, fuel type and  
 247 EURO class, is repeatedly randomly subsampled and descriptive statistics such as the  
 248 arithmetic mean calculated for each subsample. The mean of these means is then taken as  
 249 the mean and additional statistics such as confidence intervals calculated based on  
 250 distributions of these values. For this work, the process was undertaken using the R package  
 251 boot (31, 32).

### 252 **3-3. Vehicle Specific Power (VSP) calculation**

253 VSP has been shown to be a highly informative metric for the investigation of vehicle  
254 emission trends (see e.g. (29, 33)). Here, VSPs (in kW/tons) was calculated for passing cars  
255 using the methods of Jimenez-Palacios (34):

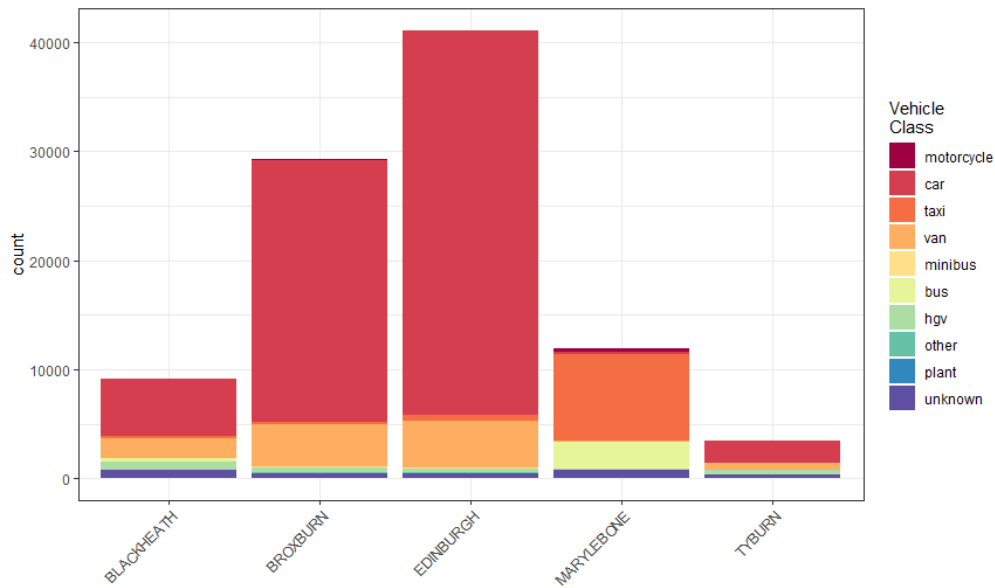
$$256 \quad VSP = speed \times (a \times accel + (g \times slope) + b) + (c \times speed^3) \quad (3)$$

257 where *speed* and *accel* are the vehicle speed (m/s) and acceleration ( $m/s^2$ ), respectively; *g* is  
258 acceleration due to gravity ( $9.81 \text{ m/s}^2$ ); and *a*, *b* and *c* are 1.1, 0.132 and 0.000302,  
259 respectively.

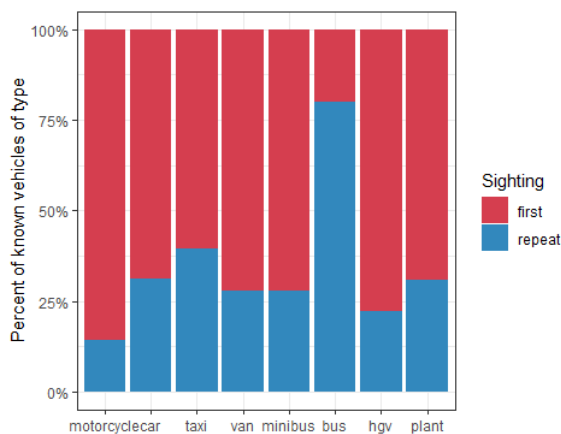
## 260 **4. Results and Discussion**

### 261 **4-1. EDAR results**

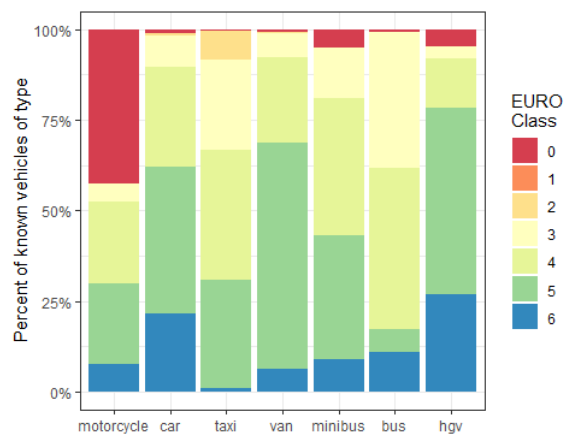
262 The vehicle counts by vehicle classification at the different field sites are shown in Figure 2.  
263 Vehicle percentages at the different sites are represented by general vehicle classification  
264 (car, taxi, bus, HGV, etc). Over the five field campaigns, a total of 94940 vehicles were  
265 measured, which included 75622 individual vehicles.



(a)



(b)



(c)

266 Figure 2: Vehicle counts by (a) vehicle classification at different sites, (b) percentage of first and repeat  
 267 sighting and (c) vehicle classification and EURO class.

268 Cars were the most commonly observed vehicle class at all studied sites except at  
 269 Marylebone, where the EDAR was measuring emissions from vehicles in a bus lane.  
 270 Approximately 75% of measurements were first time sightings of a vehicle. For most vehicle  
 271 types, the numbers of repeat sightings of the same vehicle tended to be low, i.e. between  
 272 two to four, with two main exceptions for buses and taxis. Most vehicles were EURO 4 or 5

273 (IV or V for HGVs). The highest EURO 6 (VI) proportions were observed for passenger cars and  
274 HGVs and the lowest were observed for taxis. The highest proportion of pre-EURO classified  
275 (EURO 0) vehicles were observed for motorcycles, although it is worth noting both the  
276 relatively small sample size and the fact that EURO regulations were introduced for  
277 motorcycles much later than for other vehicle types. This is an important issue because the  
278 contributions of motorcycles are most likely underestimated in most of the air pollution  
279 control programmes like the LEZ of London or CAZ of Birmingham (35).

280 Average CO<sub>2</sub> emission as estimated for this study and NO, NO<sub>2</sub>, NO<sub>x</sub> and PM emissions as  
281 determined by EDAR and CO<sub>2</sub> ratio conversions are shown for the main vehicle types of  
282 different EURO class in Figure 3. For the most part, later EURO class vehicles of a given type  
283 tend to emit less than pre-EURO and earlier EURO model vehicle of the same class, as would  
284 be expected, although these trends are not also observed for each EURO upgrade. For  
285 example, Figure 3(b) shows a gentle increasing in NO emission of buses with EURO upgrading  
286 from EURO 4 to EURO 5. Figures 3 (b)&(c) show that NO and NO<sub>2</sub> emissions decrease  
287 consistently with EURO class for petrol cars, while they initially increased (to approximately  
288 EURO 2 for NO and EURO4 for NO<sub>2</sub>, respectively) for diesel vehicles. Trends for taxis were not  
289 as pronounced as those seen for other vehicle types. Figures 3 (b)-(d) show relative high NO,  
290 NO<sub>2</sub>, and NO<sub>x</sub> emissions for EURO 1 and EURO 5 taxis and no obvious trend, although EURO 6  
291 taxis have notably highest NO<sub>2</sub> and NO<sub>x</sub> emissions among the LDVs fleet. Taxis have relatively  
292 larger emissions than the other LDVs, which could directly link to the drawbacks of  
293 accumulated mileage factor (36). For the buses, a similar interesting trend is observed for all  
294 emissions, in which EURO 4 buses have noteworthy lower emissions than the EURO 3 and  
295 EURO 5 ones, although EURO 6 buses have smallest NO, NO<sub>x</sub>, and PM emissions among the  
296 other buses. In terms of PM emission, Figure 3(e) shows a descending trend in almost all



297 vehicles, except taxis and HGVs, in which EURO 6 vehicles have smallest PM emission among  
298 the others. For PM emission of taxis, EURO 3 taxis have the highest emission among the  
299 others. Van and HGV trends are generally downward but less obvious, most likely reflecting  
300 the smaller sample sizes.

301 PM and NO<sub>x</sub> emissions of heavy-duty diesel vehicles (HDDVs) are significant environmental  
302 challenges. The latest emission standards oblige HDDV manufacturers to develop new  
303 treatment and after-treatment technologies (see for example (37, 38)). Diesel particulate  
304 filters (DPFs) and selective catalytic reduction (SCR) technologies have been applied to  
305 mitigate tailpipe PM and NO<sub>x</sub> emissions of HDDVs (39). DPFs catch the soot and other  
306 combustion particulate products by physical trapping with solid filters. Earlier HDDV DPFs  
307 used active filter regeneration technologies, increasing the temperature of the exhaust up to  
308 500°C to burn off the soot in the DPF, while the newer-to-market DPFs employed passive  
309 regeneration methods to remove collected PM from the filled DPFs (39, 40). In the later  
310 technologies, the exhaust temperature in the after-treatment device is raised to enhance  
311 engine-out conversion of NO to NO<sub>2</sub>, and then NO<sub>2</sub> is used as the catalyst to oxidize stored  
312 PM.

313 The emission trends of HGVs and buses in Figure 3 reflects the development of HDDV  
314 treatment and after-treatment technologies. Figure 3(a) shows that EURO 6 (VI) HGVs have  
315 higher CO<sub>2</sub> emission factors than EURO 5 (V) and EURO 4 (IV) ones. Also, EURO 6 (VI) HGVs  
316 have higher and lower NO<sub>2</sub> and NO emission factors than EURO 5 (V) and EURO 4 (IV) ones,  
317 respectively. It seems that converting engine out NO to NO<sub>2</sub> and also oxidizing stored PM in  
318 the HDDV DPFs was more efficiently carried out in EURO 6 (VI) HGVs compared with the older  
319 EURO HGVs. The new technologies could significantly reduce HDDV tailpipe NO<sub>x</sub> emission,

320 while similar was not observed for the exhaust PM emission. Grigoratos et al. showed that  
321 the efficiency of the new HDDV treatment and after-treatment PM abatement technologies  
322 inversely correlate with vehicle speed, and higher PM emissions at lower speeds are most  
323 likely linked to lower exhaust system operating temperatures under these conditions (14).  
324 Hence, the observed drawback in tailpipe PM emission of EURO 6 (VI) HGVs could be  
325 attributed to the impairing of HGVs treatment efficiency in urban environments. For the  
326 buses, it seems that the recent technologies could control both NO<sub>x</sub> and PM tailpipe  
327 emissions even in urban areas. However, the employed treatment technologies for reducing  
328 NO<sub>x</sub> emission were more efficient than that for PM emission.

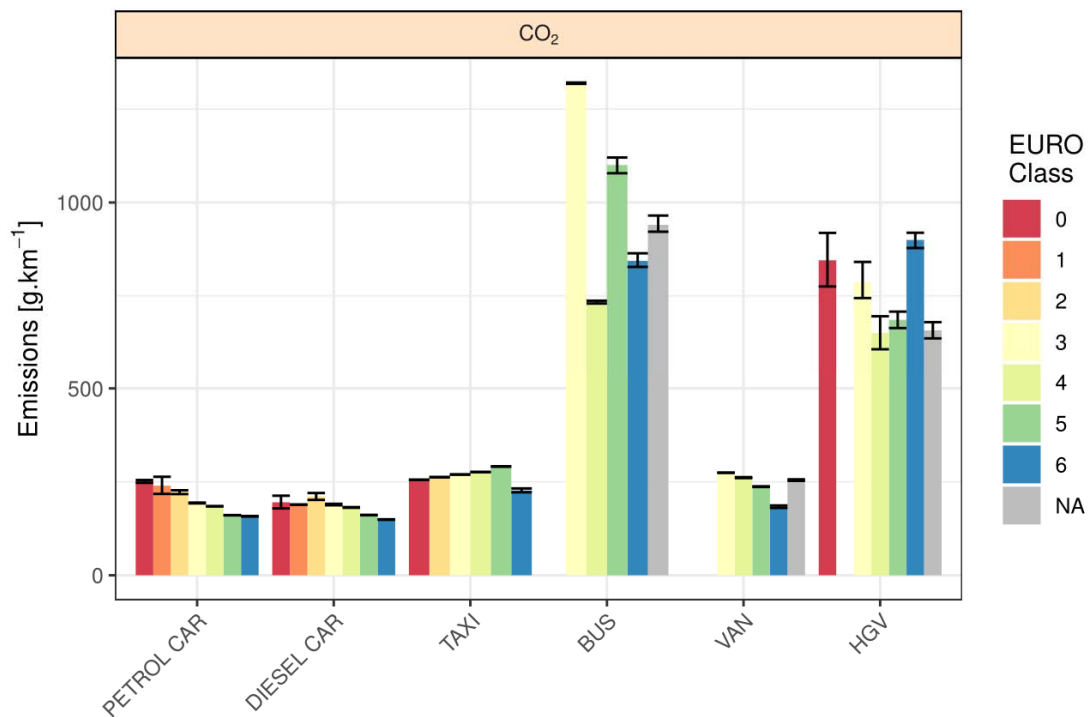
329 In terms of the most recent EURO upgrade, EURO 5 to EURO 6, the EDAR results suggest  
330 emissions (most notably NO and NO<sub>x</sub>) are decreasing for most vehicle types, although there  
331 are some noteworthy exceptions. EURO 5 to EURO 6, taxi and possibly HGV NO<sub>2</sub> emissions  
332 increase, although the trend for the latter is less certain as indicated by relative size of error  
333 bars. EURO 5 to EURO 6, PM could be increasing for cars, vans and most notably HGVs  
334 although these are perhaps the most uncertain trends. Some of the highest emissions were  
335 observed for vehicles that do not appear to be registered in the vehicle information archives  
336 and of unknown EURO class. These were typically buses, vans and HGVs and labelled 'NA' in  
337 Figure 3.

338 The PEMS experiments of O'Driscoll et al. report 86-96% reductions in the NO<sub>x</sub> emissions of  
339 petrol cars compared with the diesel ones (41), for comparison, in this paper 50-71% reduction  
340 is observed (see Figure 3(d)). Figure 3(d) shows that EDAR-reported NO<sub>x</sub> emissions from EURO  
341 6 diesel cars (0.52 g/km) were 2.7 times higher than that for petrol cars (0.19 g/km).  
342 However, O'Driscoll et al. observed that the tailpipe emission of NO<sub>x</sub> in diesel light-duty

343 vehicles, i.e. 0.44 g/km, was 11 times higher than for petrol ones (0.04 g/km) (41). Lower  
 344 reported  $\text{NO}_x$  from petrol cars could reflect differences in the distributions of emissions from  
 345 petrol and diesel cars and measurement techniques. PEMS provides an average emission  
 346 across a longer journey while EDAR and other VERSSs provide a measure of vehicle-related  
 347 emissions at the deployment site.

348 Figure 3 indicates an interesting trend in the on-road emission factors. While the study of  
 349 Carslaw et al. for 2011 (23), a study using an across-road VERSS, reports little change in  $\text{NO}_x$   
 350 emissions from EURO 1 to EURO 4 cars, Figure 3 (d) presents a 32 to 42% reduction in the  
 351  $\text{NO}_x$  emission of cars from EURO 4 to EURO 6. Moreover,  $\text{NO}_x$  emission of HGVs and buses  
 352 reduce 57% and 65% from EURO 4 to EURO 6, respectively, whereas Carslaw et al. report on  
 353 relatively stable emissions from EURO 1 to EURO 4 (23).

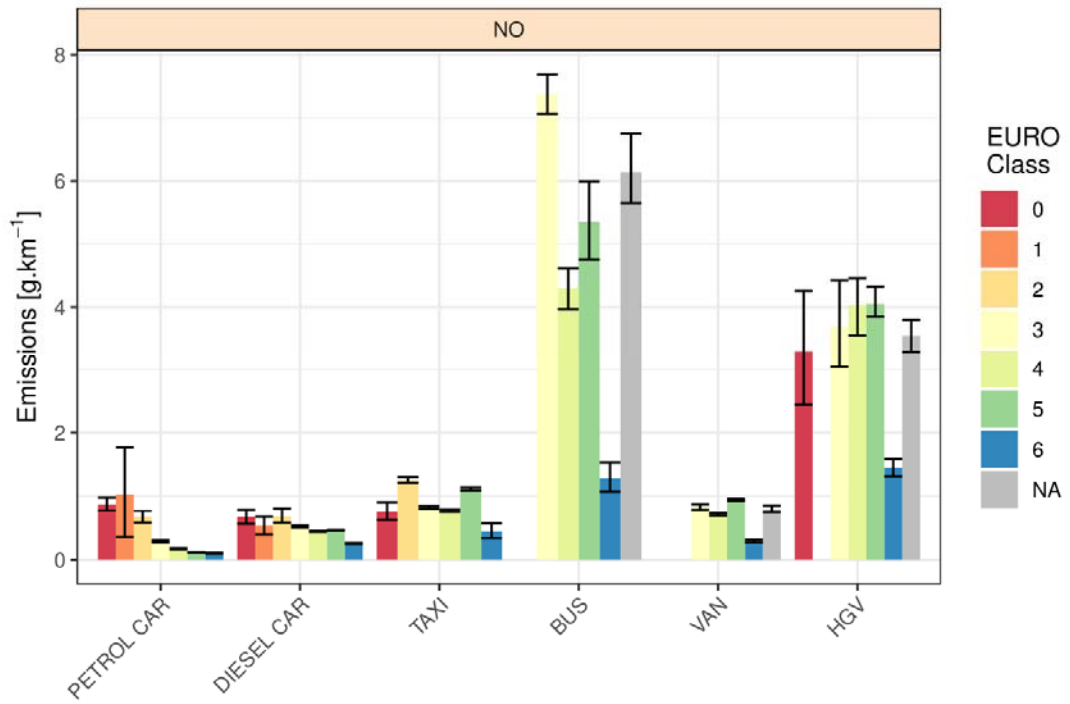
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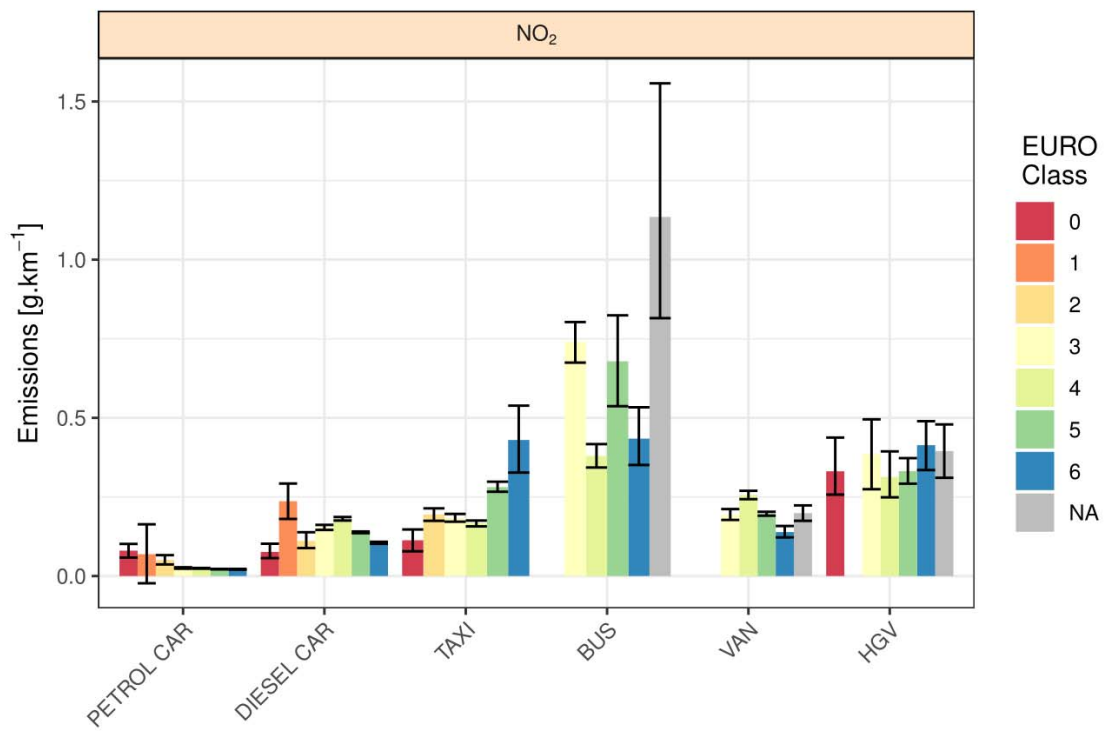
(a)



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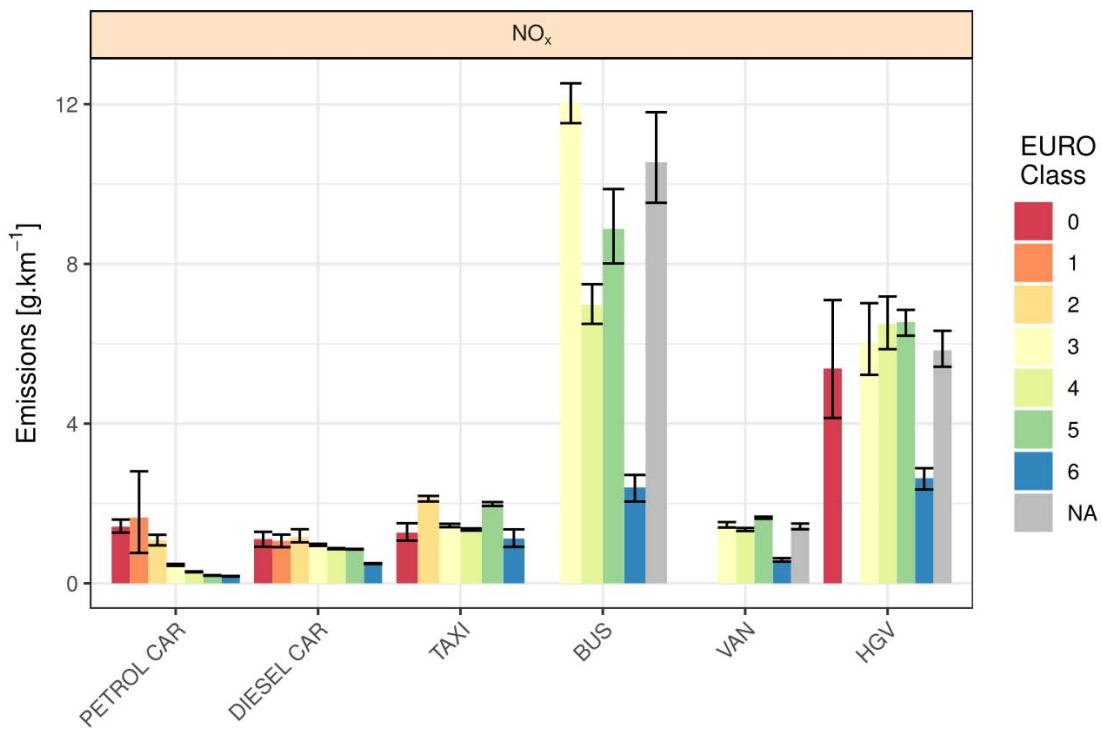
(b)



359

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(c)

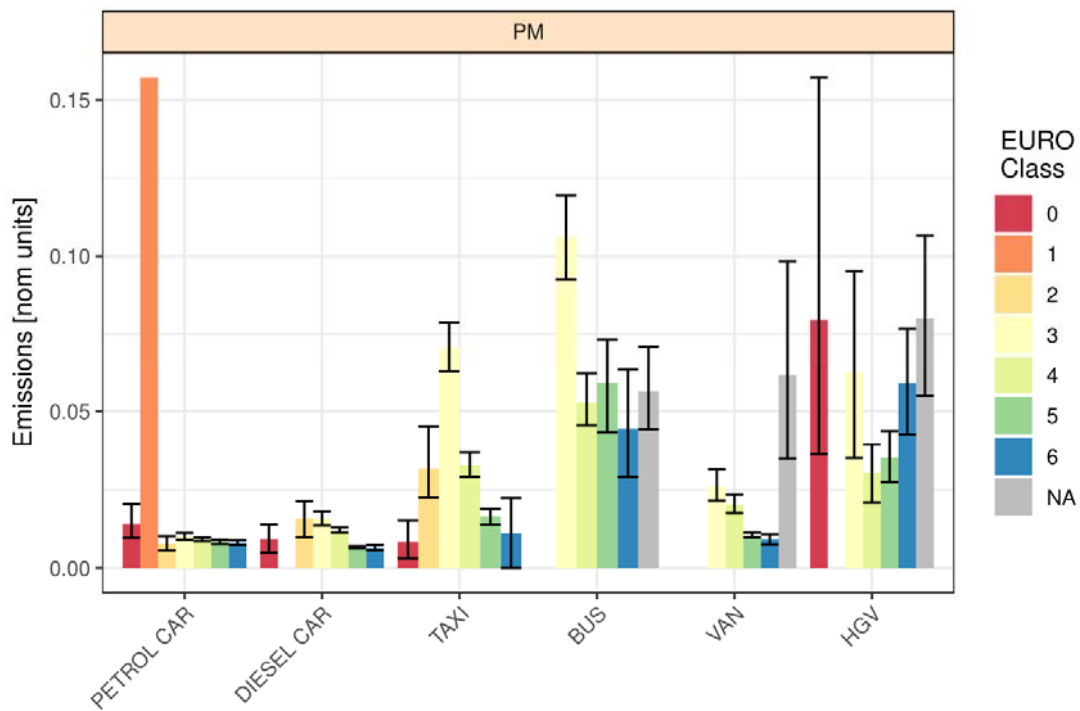


361

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(d)

363



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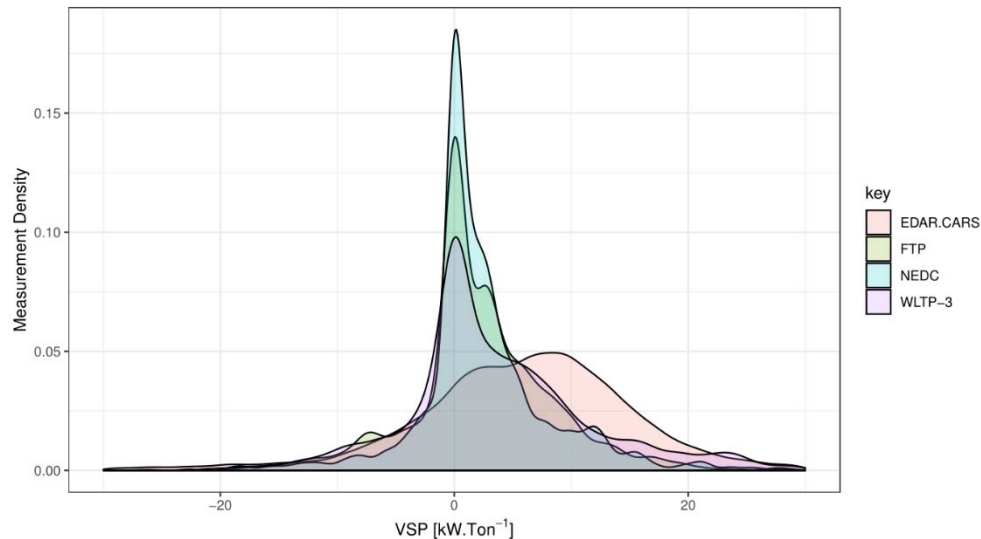
365 (e)

366 *Figure 3. Average of (a) CO<sub>2</sub>, (b) NO, (c) NO<sub>2</sub>, (d) NO<sub>x</sub> and (e) PM emissions from vehicles*  
367 *observed during the EDAR campaigns. Vehicles with unknown EURO classes were labelled 'NA'*  
368 *here.*

369 Further breakdowns of vehicle emissions trends are presented in Supplementary files,  
370 including versions of the plots shown in Figure 3 with each vehicle type is shown on a discrete  
371 scale to provide easier by-EURO-class comparisons for the different vehicle types  
372 (Supplementary Materials Figure S1).

373 Figure 4 compares the VSP distributions of the New European Driving Cycle (NEDC) and  
374 Worldwide harmonised Light vehicles Test Procedure (WLTP) regulatory dynamometer drive  
375 cycles that EURO 1-5 and EURO 6 cars are tested on and the VSP calculated for speed and  
376 acceleration measurements for cars in the EDAR dataset. This observation is not unique to  
377 EDAR. Borken-Kleefeld et al. reported highly similar findings for the larger pan-European  
378 dataset of OPUS RSD measurements collected by CONOX (42). Here, there is a clear  
379 difference between the test cycle and EDAR sample VSP distributions. The test cycles tend to  
380 be dominated by lower power events with a VSP frequency that is highest very near to  
381 0kW/ton while the EDAR measurements were on average collected under higher power  
382 conditions (frequency maxima about 10 kW/ton). The VSP distribution for the EPA Federal  
383 Test Procedure (FTP) is also included in Figure 4 to show that this difference is not specific to  
384 European test cycles. It should be noted that VSP distribution is the FTP-75 test cycle with the  
385 engine-off period excluded so comparison is with vehicle operating times only.

386



387 *Figure 4. Comparison of vehicle specific power (VSP) distributions for EDAR data collected in the UK*  
 388 *EDAR campaigns (this study) and VSP distributions for the other standard driving cycles including New*  
 389 *European Driving Cycle (NEDC), Worldwide harmonised Light vehicles Test Procedure (WLTP) and*  
 390 *Federal Test Procedure (FTP) regulatory emissions testing procedures.*

391 It is unsurprising that vehicle emissions measured by EDAR and RSD are both reported to be  
 392 significantly higher than vehicle emissions as determined in test procedures (see e.g. (43,  
 393 44)). This is due to the requirement that VERSS measurements are made under conditions of  
 394 some load on the engine, typically achieved by the selection of sites where vehicle tend to be  
 395 acceleration (e.g. after signalised stops, on slip-roads or exiting roundabouts) and/or on  
 396 upward inclines (25). This situation creates a number of questions, most notably:

- 397 - Could differences between regulatory test and on-road VERSS emissions
- 398 measurements simply reflect the different engine loadings the vehicles are under?
- 399 - Are the VERSS measurements representative of on-road emissions?

400 To address the first of these questions the diesel car subset of the EDAR data was  
 401 reweighted, EURO 1 to EURO 5 to the NEDC VSP distribution and EURO 6 to the WLTP VSP  
 402 distribution to provide a more direct basis for comparison. Figure 5 (a) shows the  $\text{NO}_x$

403 emissions of diesel cars for selected makes and EURO classifications as determined by EDAR  
 404 prior to reweighting. Here, all observed  $\text{NO}_x$  emissions are several times their associated  
 405 emission standard, e.g. all shown EURO 6 diesel cars exceed the EURO 5 standard and several  
 406 even exceed the EURO 3 standard. Based on the inspection of data in this fashion it would be  
 407 easy to conclude that vehicles on-road are far worst emitters than in tests. However, if the  
 408 data is reweighted according to the VSP distribution of the appropriate emission test drive  
 409 cycle (as in Figure 5 (b)), corrected emissions are all much lower. For example, while none of  
 410 the measured EURO6 diesel vehicles emitted less than the EURO 6 standard, most were less  
 411 than EURO 5 standard, indicated much less pronounced differences.

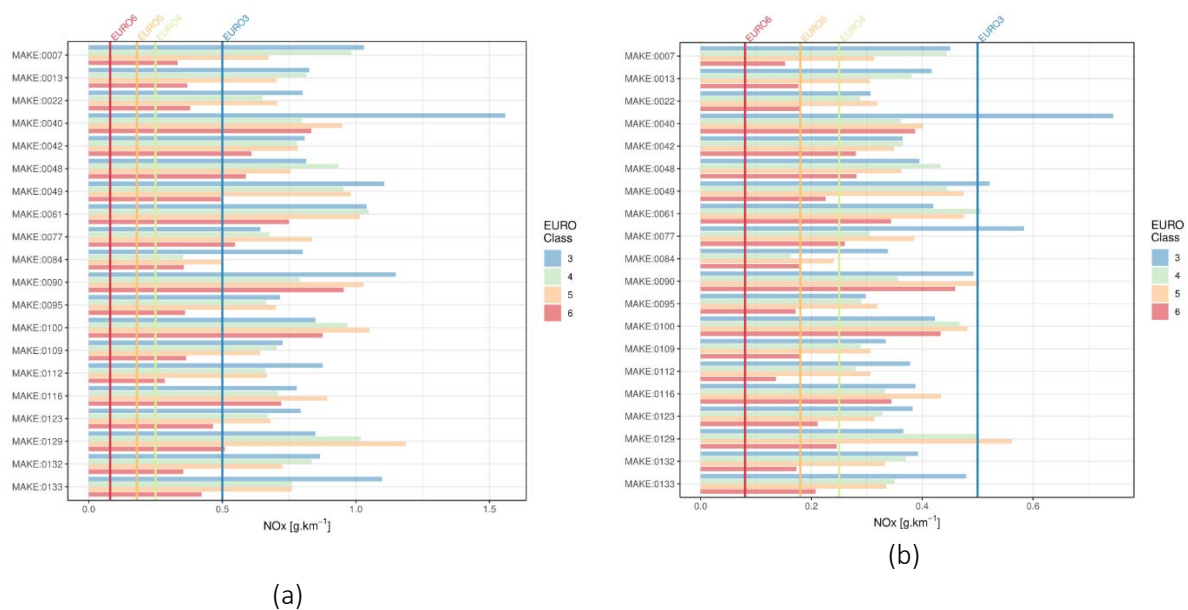


Figure 5. Average  $\text{NO}_x$  ( $\text{g}/\text{km}$ ) emissions of EURO 3 to EURO 6 diesel cars as observed during the UK EDAR campaigns (a) before and (b) after reweighting of measurements using NEDC and WLTP VSP distributions for EURO 3-5 and EURO 6 cars, respectively. Solid lines indicate associated EURO 3 to EURO 6 emissions standards.

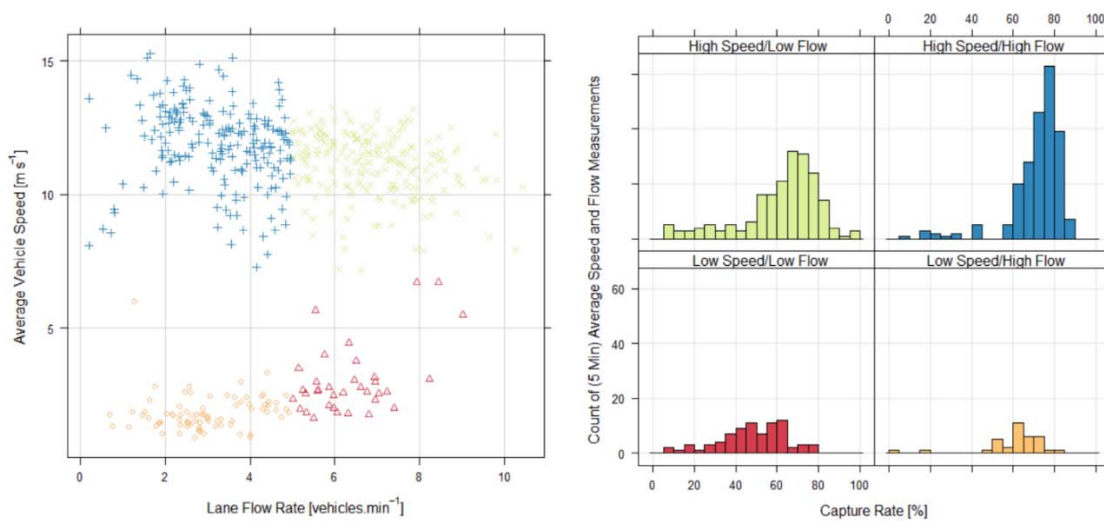


412 There are however two related caveats: Firstly, this is probably still an over-estimation of NO<sub>x</sub>  
413 emissions. The VSP distributions of the measurements are corrected but not the fuel  
414 consumption estimates used to calculate g/km NO<sub>x</sub>. Doing that would likely increase the  
415 magnitude of the corrections for most vehicles. And, secondly, whatever correction strategy  
416 is applied, there is an assumption that any misalignment of emissions and (speed and  
417 acceleration based) VSP measurements is not introducing bias. With that in mind, VSP  
418 corrections should be viewed as indicative rather than quantitative unless such bias is  
419 addressed.

420 With regard to the question of how representative VERSS measurements are of on-road  
421 emissions, it is clear that the measurements are of real vehicles as part of their actual on-  
422 road journeys. So, it would seem counter-intuitive to state otherwise. Some have even gone  
423 so far as to describe them as the 'real "real-world" emissions'. However, there are elements  
424 of on-road driving that all VERSSs (EDAR and RSD alike) under-report. For example, because  
425 VERSSs measure emissions by isolating a plume profile, driving behaviours like deceleration  
426 that produce little or no obvious plume are often relatively under-reported. Similarly,  
427 emissions from idling vehicles and stop-start driving during congested periods are often also  
428 under-reported because the gaps between successive vehicles are not wide enough to  
429 provide clear measurements of leading vehicles exhaust plumes.

430 Figure 6 illustrates this issue by comparing data capture rates for an example VERSS under  
431 different driving conditions, measured independently using local traffic data. There is an  
432 obvious bias in capture rate of the system towards both higher counts and capture rates  
433 under high speed and high flow conditions. It is however emphasized here that this is not an  
434 EDAR specific problem, but a bias that needs to be considered for all VERSS type instruments.

435 The bias is driven by the fact that all current design VERSSs (both down facing systems like  
 436 EDAR and across-road systems like RSD) need a clean vehicle drive-through, followed by a  
 437 good gap (of the order of several seconds) before the next vehicle to make a plume  
 438 measurement they can reliably quantify. Both requirements are simply less likely under more  
 439 congested driving conditions. This means that while VERSSs do indeed provide real-world  
 440 emission measurements, simply averaging and reporting emissions as observed in any VERSS  
 441 campaign will not explicitly produce an absolute measure of local emissions. If truly locally-  
 442 representative emissions data is required, the VERSS data require some form of correction,  
 443 e.g. reweighting on the basis of the VSP distribution of similar vehicles in the local fleet/study  
 444 area may be required to take into account such sampling bias.



445

446 *Figure 6. Example VERSS capture rates under different driving conditions.*

447

448 **4-2. Using EDAR data to assess low emissions zones**

449 During the last decade, three different zoned abatement strategies were considered in UK  
 450 metropolitan areas to reduce the numbers of higher polluting vehicles entering designated

451 areas. The first scheme implemented was the LEZ of London, which has covered most of  
452 Greater London for 24 hours a day, 7 days a week since February 2008, with the aim of  
453 reducing the exhaust gas emissions of diesel-powered commercial vehicles. Under the LEZ all  
454 the light-duty vehicles and motorcycles can freely enter the enforcement zone, but larger  
455 vans and minibuses that do not meet EURO 3 (or III) or later emission standards, and lorries,  
456 buses, and coaches that do not meet EURO 4 (or IV) or later emission standards are all  
457 charged to enter the enforcement zone.

458 The ULEZ was established in April 2019 to further reduce the number of worst polluting  
459 vehicles. Its stated aim is to achieve a 20% reduction in the vehicular emissions and drop the  
460 number of worst polluting vehicles from 35,600 to 23,000 (10). ULEZ is a more restricted  
461 scheme compared to the LEZ one, whereby motorcycles and petrol cars can freely enter the  
462 ULEZ areas if they meet or exceed EURO 3 and 4 standards, respectively. Diesel cars and  
463 vans, Buses, coaches and Lorries must meet or exceed EURO 6 standards. In addition to  
464 London, other metropolitan areas within the UK have been struggling with air pollution  
465 concerns, and so newer more restrictive schemes are now being implemented both in  
466 London and elsewhere. For example, the city of Birmingham within the West Midlands  
467 metropolitan area has a CAZ scheme due to be established in 2021. In addition to  
468 Birmingham, the cities of Leeds, Liverpool, Bristol, Bath and Southampton will also be  
469 introducing CAZs. CAZs are being set up in response to concentrations of NO<sub>2</sub> which exceeds  
470 the European Union limitations (45). The CAZ in Birmingham is due to be a 'type D' CAZ,  
471 which is designed principally based on the type of the fuel of vehicles, whereby all petrol and  
472 diesel vehicles should meet or exceed EURO 4 and 6 emission standards to freely enter the  
473 CAZ area, respectively. Whilst all vehicles should meet the EURO standards, certain vehicles

474 are excluded from the scheme. Motorcycles are currently completely free to enter the CAZ  
475 enforcement area without any restrictions.

476 Based on the results of the present study on the emission performance of different vehicle  
477 classes with different EURO standards, a new measure is introduced in this study to evaluate  
478 the real potential of UK abatement strategies. EURO Updating Potential factor of pollutant  $p$   
479 ( $EUP_p$ ) is defined as:

$$480 \quad EUP_p = \sum_i \alpha_i \sum_j q_{i,j} \times e_{i,j,p} \quad (4)$$

481 where  $\alpha_i$  is the contribution of vehicle class of  $i$  in the total transportation fleet,  $q_{i,j}$  is the  
482 contribution of vehicles with the emission standard of EURO  $j$  in the vehicle class of  $i$ , and  
483  $e_{i,j,p}$  is the relatively improvement indices in the emission factor of pollutant  $p$  corresponds  
484 for vehicle class  $i$  with emission standard of EURO  $j$ . It is assumed the total fleet  
485 contributions which did not meet the Euro emission standards will be updated by the latest  
486 EURO emission standard, i.e. EURO 6, to assess the real potential of considered strategies in  
487 the improvement of regional air quality. Therefore, the relative improvement indices of  
488 pollutant  $p$  for every vehicle class  $i$  is defined as:

$$489 \quad e_{i,j,p} = \frac{EF_{i,j,p} - EF_{i,6,p}}{EF_{i,j,p}} \quad (5)$$

490 where is the  $EF_{i,j,p}$  is the emission factor of pollutant  $p$  emitted by vehicle class of  $i$  with  
491 emission standard of EURO  $j$ . The relative improvement indices of the pollutants  $NO_x$ ,  $CO_2$ ,  
492 and PM are calculated using the data presented in the Figure 3. The EUP factors calculated  
493 for different abatement strategies are illustrated in Table 1.

494 *Table 1. The EUP factors (in %) for different abatement strategies and different pollutants.*

<i>Scheme</i> <i>Pollutant</i>	<i>LEZ</i>	<i>ULEZ</i>	<i>CAZ</i>
<i>NO<sub>x</sub></i>	<i>7.4</i>	<i>32.8</i>	<i>36.5</i>
<i>PM</i>	<i>2.3</i>	<i>17.9</i>	<i>14.5</i>
<i>CO<sub>2</sub></i>	<i>0.2</i>	<i>10.3</i>	<i>7.6</i>

495 It indicates that the LEZ has the smallest EUP factors compared to the two other types of low  
 496 emissions zone. This is expected because the LEZ was the earliest and least restrictive of  
 497 these strategies. The CAZ type 'D' emissions zone could reduce more than 30%, 14% and 8%  
 498 of the NO<sub>x</sub>, PM and CO<sub>2</sub> vehicular emission factors, respectively. The ULEZ is expected to  
 499 have a better performance by comparison with the others for CO<sub>2</sub> and PM, but the type 'D'  
 500 CAZ is expected to provide the largest NO<sub>x</sub> reductions.

501

## 502 5. Conclusions

503 In this study data collected in five EDAR deployments in the UK, in 2016 and 2017, were  
 504 analysed. Subset according to vehicle type, fuel type and EURO class, the findings provide  
 505 valuable evidence on UK vehicle fleet emissions. In terms of emission trends, it is observed  
 506 that NO and NO<sub>x</sub> vehicle emissions are typically very similar or more often better for the main  
 507 vehicle types for EURO 6 vehicles by comparison to their EURO 5 counterparts, which is  
 508 obviously an encouraging finding given trends EURO 3 to 5. However, some increases were  
 509 observed for NO<sub>2</sub> EURO 5 to EURO 6 for (diesel) Taxis and possibly HGVs, and perhaps most  
 510 concerningly an increase in PM emissions EURO 5 to EURO 6 for HGVs. Also noteworthy was  
 511 the observation that unknown vans, buses and HGVs, those for which there was little or no

512 information in public archives, were often the dirtiest vehicles in their classes, suggesting that  
513 where counts of such vehicles are high they could be making a significant local contribution  
514 to emissions.

515 During this study, an assessment of the differences of VERSS data compared to regulatory  
516 driving cycle standards was conducted. The relatively high emissions of vehicles as reported  
517 by other VERSSs has, for example, received significant media attention in recent times.  
518 However, EDAR and other VERSSs all made emissions measurements at on average higher  
519 engine loads than current regulatory tests, so emissions would be expected to be higher.  
520 Using VSP weighting, we provide an indication of the magnitude of this bias and a closer  
521 estimate of the regulatory test/on-road emissions gap.

522 Finally, a new factor 'EUP' was applied here to evaluate the real potential of UK abatement  
523 strategies to reduce transport-related air pollution. The EUP factors were calculated based on  
524 the assumption that all banned vehicle will be replaced with vehicles of the latest EURO  
525 standard. Our results indicate that LEZ has the smallest potential to improve the regional air  
526 quality compared to the ULEZ and CAZ schemes. However, it is suggested to reconsider CAZ  
527 scheme from the global warming pollutant point of view, in which it has smallest EUP factor.

528

529

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539 workshop (01 August 2016) regarding unit conversion methods.

540

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