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

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Abstract.

This paper reports upon and analyses vehicle emissions measured by the Emissions Detecting and Reporting (EDAR) system, a Vehicle Emissions Remote Sensing System (VERSS) type device, used in five UK based field campaigns in 2016 and 2017. In total *94940* measurements were made of *75622* individual vehicles during the five campaigns. The measurements are subset into vehicle type (bus, car, HGV, minibus, motorcycle, other, plant, taxi, van, and unknown), fuel type for car (petrol and diesel), and EURO class, and particulate matter (PM), nitric oxide (NO) and nitrogen dioxide (NO_2) are reported. In terms of recent EURO class emission trends, NO and NO_x emissions decrease from EURO 5 to EURO 6 for nearly all vehicle categories. Interestingly, taxis show a marked increase in NO_2 emissions from EURO 5 to EURO 6. Perhaps most concerningly is a marked increase in PM emissions from EURO 5 to EURO 6 for HGVs. Another noteworthy observation was that vans, buses and HGVs of unknown EURO class were often the dirtiest vehicles in their classes, suggesting that where counts of such vehicles are high, they will likely make a significant contribution to local emissions. Using Vehicle Specific Power (VSP) weighting we provide an indication of the magnitude of the on-site VERSS bias and also a closer estimate of the regulatory test/on-road emissions differences. Finally, a new 'EURO Updating Potential' (EUP) factor is introduced, to assess the effect of a range of air pollutant emissions restricted zones either currently in use or marked for future introduction. In particular, the

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

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

1. Introduction

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

Typically, the most important air pollutants from a health perspective are particulate matter (PM) and nitrogen dioxide (NO_2). Vehicle exhaust emissions are the major source of urban NO_2 and a significant source of PM. Hence real-world vehicular emissions of these pollutants are vitally important to be able to understand and hence reduce air pollutant concentrations. Since NO_2 rapidly interconverts between nitric oxide (NO) under typical photochemical conditions in the urban atmosphere, it is also important to measure the vehicular emissions of NO in addition to NO_2. From a climate perspective, it is also important to monitor vehicular emissions of carbon dioxide (CO_2).

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

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

In the second sub-category, local actions are implemented to reduce or restrict vehicle activities in the most polluted areas or encourage the use of alternative vehicle technologies. The UK Low Emission Zones (LEZs), Ultra Low Emission Zones (ULEZs), and Clean Air Zones (CAZs), described and discussed in further in Section 4.2, are examples of major interventions. Other options to reduce urban pollution include public transport service expansions, alternative vehicle infrastructure development (e.g. electric vehicle charging points and alternative fuelling stations), and traffic flow management and calming activities (9). Previously, it has been shown that implementing the LEZ in London has had notable impacts upon PM concentration, while the variation in the concentration of Nitrogen Oxides (NO_x) seems to be insignificant (10, 11).

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

A number of reports and studies have been published on the emission performance and emission characteristics of the vehicles with different EURO standards. For example, Kwon et al. studied the characteristics of six EURO 6 light-duty diesel vehicles using a PEMS (16). They observed that the status of the air condition system of the vehicle, on or off, as well as outdoor ambient temperature could significantly impact on NO_x emission factor of the studied vehicles. Chen et al. used chassis dynamometer to assess the role of several factors on the emission of one EURO VI diesel city bus (17). Their results show that the emission factors are influenced to some extent by different factors, e.g. fuel type, driving behaviour and road conditions. Lujan et al. used PEMS to study the emission performance of a EURO 6 light-duty diesel vehicles under different speeds (18). Results show that acceleration at low speeds leads to higher NO_x emissions compare to a similar action at high speeds. Simonen et al. conducted different experiments in the laboratory and real-world conditions on three EURO 6 light-duty vehicles (19). Their results show notable differences between emissions under real-world and controlled conditions. The same was observed in the study of Triantafyllopoulous et al., when the CO_2 and NO_x emissions of three EURO 6 diesel vehicles were investigated under the controlled and on-road conditions (20). Mere et al. also used PEMS to study the high instantaneous NO_x emissions from Euro 6 diesel passenger cars (21). They investigated the operation of three SUV diesel passenger cars and found that high instantaneous NO_x emission contributes a large amount of total NO_x emission. Grigoratos et al. used PEMS to study the emission performance of five EURO VI heavy-duty vehicles under typical driving conditions (14). Results illustrated overall lower emissions compared to older technology heavy-duty vehicles.

However, much of published literature derives from dynamometer and PEMS studies which tend to be limited to small numbers of vehicles, and few provide a systematic comparison of multiple vehicle types and emissions classes. One noteworthy exception is the analysis of PEMS data from 149 EURO 5 and 6 diesel, gasoline and hybrid light-duty vehicle reported by O'Driscoll et al [21]. This study provides a robust estimate of the relative scales of NO_x emissions form EURO 6 diesel and gasoline vehicles. However, a substantial number of real-world PEMS studies would be required to achieve a comprehensive understanding on the emission performance of vehicles of different EURO standards.

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

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

VERSSs have been employed in the UK street networks since almost two decades ago to drive a detailed picture of the on-road vehicle emissions. One of the earliest VERSS campaigns in UK has been conducted by the University of Leeds and Enviro Technology plc between 2007 and 2010 (23). The most interesting finding of that study was that NO emission in diesel passenger cars had not reduced as much as previously estimated. The first direct measurements of other nitrogen oxides in the UK using VERSS had been conducted by Carslaw et al (24). They observed little evidence of NO_x emission reduction from all types of diesel vehicles. Another VERSS campaign had been conducted in two UK cities, i.e. York and London, in 2017 and early 2018 (25). Results show that NO_2 emissions tend to decrease with increasing vehicle mileage. Grang et al., conducted VERSS campaigns in 10 regions and 26 sites throughout the UK in 2017 and 2018 (26). The main finding of their study was that NO_x emission in passenger cars were found to be significantly dependent on ambient temperature.

In this paper we report on vehicular emissions measured by one of the infrared laser based VERSS, the Emissions Detection and Reporting (EDAR) system, which was developed and commercialized by Hager Environment and Atmospheric Technologies (HEAT). A schematic diagram of EDAR is provided in Figure 1. The EDAR has a number of unique features by comparison to conventional across-road VERSS, most notably: (1) The EDAR measures species using Differential Absorption LIDAR (DiAL), a technique which is widely reported to be more sensitive, selective and less susceptible to drift than the conventional absorption spectroscopy-based methods employed by other VERSSs (15, 27, 28). (2) EDAR measures NO_2 directly. Many other commercialised instruments, for example older RSDs, measured NO and estimated NO_2 and NO_x by assuming fixed ratio contributions, a practice highlighted as potentially misleading (29). (3) Although, unlikely to be unambiguous, the approach could provide a better estimate of vehicle-based particulate matter (PM) emissions than conventional VERSSs because there are some early indications that it is more sensitive to finer PM than the conventional optical methods used by other VERSSs (See (28)). (4) All

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

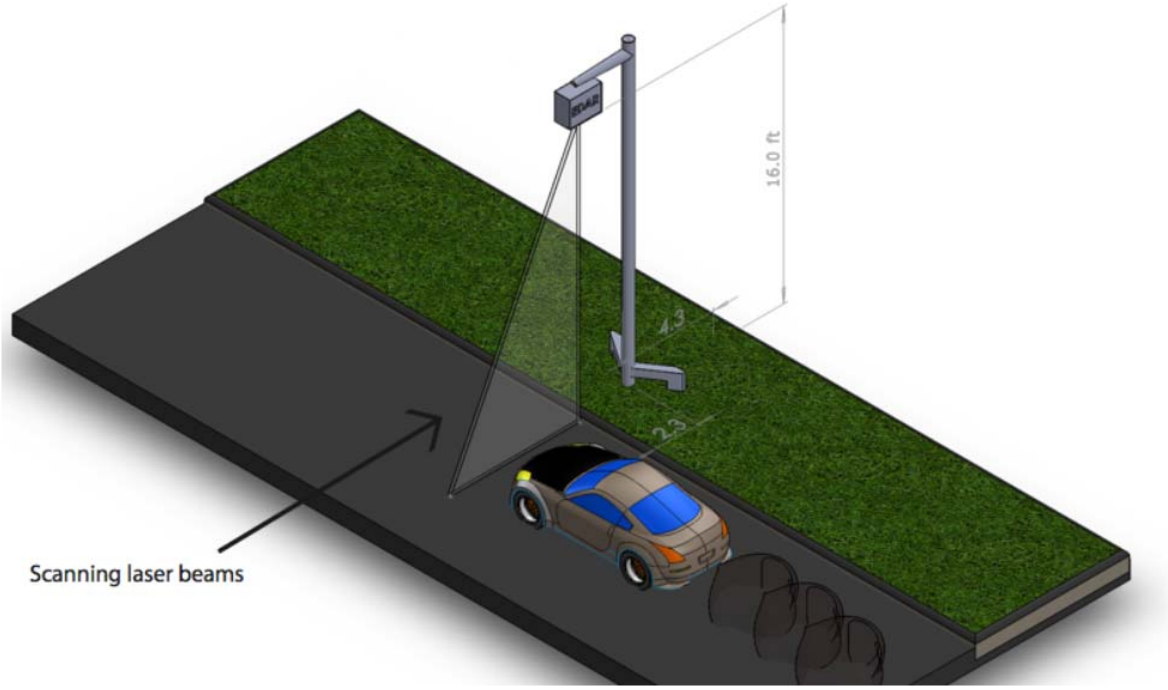


Figure 1. Schematic picture of HEAT EDAR (https://www.heatremotesensing.com).

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

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

While across-road VERSS studies have already provided some information of these topics (23-26, 29), data from an independent source and technique like EDAR expands the evidence base and increases the confidence in consistent observations. EDAR also potentially provides more comprehensive and direct comparison of fleet classes with very different exhaust positions and configurations, e.g. motorcycles, cars, buses and HGVs. The results of this study can be used to inform policies aimed at improving air quality and reducing greenhouse gas emissions.

2. EDAR deployment in UK

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

3. Materials & Methods

3-1. EDAR data

The data obtained from the EDAR system are passing vehicle emission measurements of CO_2, NO, NO_2, and PM, exhaust temperature, vehicle registrations captured by Automotive Number Plate Recognition (ANPR) system, collocated speed camera measurements of speed and acceleration, and simultaneous ambient information from a weather station unit. After the field campaigns were completed, the ANPR records were used to merge this and other vehicle specific data from vehicle fleet registration databases (Driver Vehicle Licensing Authority (DVLA) and Motor Vehicle Registration Information System (MVRIS) for 2016 measurements and Society of Motor Manufacturers Traders (SMMT) for 2017 measurements), and this was used to subset the vehicle emissions data according to vehicle type (bus, car, HGV, minibus, motorcycle, other, plant, taxi, van, and unknown), fuel type for car (petrol and diesel), and EURO class. For further information regarding the performances of the EDAR and ANPR, please see Ropkins et al. (28) and Sulaiman et al. (30), respectively. Although the measured fleets included a small number of alternatively fuelled vehicles, the numbers were not sufficient for statistically robust comparison and analysis is restricted to petrol and diesel vehicles.

3-2. Data analysis

EDAR data was converted from the pollutant/CO_2 ratio form provided by the EDAR manufacturer into the grams-per-kilometre (g/km) form and analysed using the following procedures. Gaseous species were converted to g/km using the following equation:

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

where n is the species (CO, NO, NO_2), $ratio_{[n]/CO_2}$ is the EDAR measurement, $[CO_2]_{g/km}$ is the CO_2 (g/km) emission rate derived from the available datasets, and $mwt_{[n]/CO_2}$ is the molecular weight ratio of n to CO_2. NO_x emissions were calculated in line with the European vehicle type approval definition of NO_x (g/km) by the following equation:

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

where $mwt_{NO_2/NO}$ is the NO_2/NO molecular weight ratio, i.e. approximately 46/30. PM was reported by EDAR in nanomole/mole. As an alternative to reporting emissions in these molar units, we used the PM comparison plot generated from data collected as part of the PEMS drive-through EDAR evaluation exercise of the Birmingham and London EDAR study (28) as a field calibration to convert the EDAR nanomole/mole outputs to gram of particulate per kilogram CO_2 equivalents, before applying the above method to derive an estimate of PM emissions in g/km units.

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

3-3. Vehicle Specific Power (VSP) calculation

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

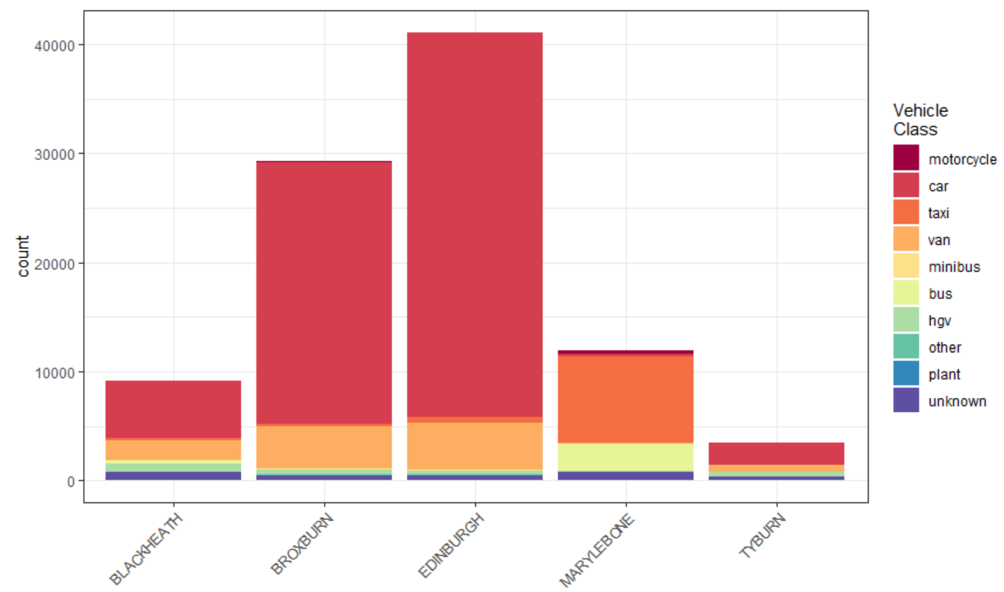
$$VSP = speed \times (a \times accel + (g \times slope) + b) + (c \times speed^3) \quad (3)$$

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

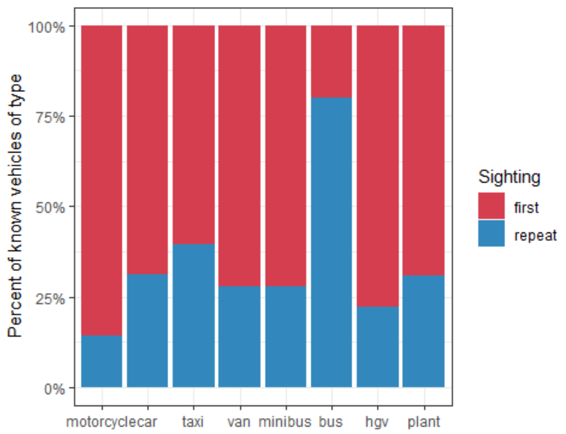
4. Results and Discussion

4-1. EDAR results

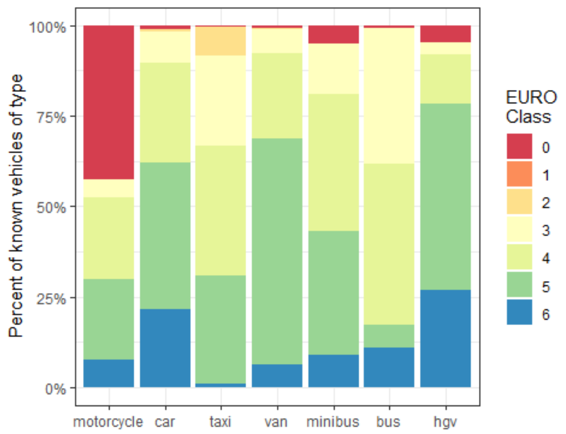
The vehicle counts by vehicle classification at the different field sites are shown in Figure 2. Vehicle percentages at the different sites are represented by general vehicle classification (car, taxi, bus, HGV, etc). Over the five field campaigns, a total of 94940 vehicles were measured, which included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



(a)



(b)



(c)

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

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

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

Average CO_2 emission as estimated for this study and NO, NO_2, NO_x and PM emissions as determined by EDAR and CO_2 ratio conversations are shown for the main vehicle types of different EURO class in Figure 3. For the most part, later EURO class vehicles of a given type tend to emit less than pre-EURO and earlier EURO model vehicle of the same class, as would be expected, although these trends are not also observed for each EURO upgrade. For example, Figure 3(b) shows a gentle increasing in NO emission of buses with EURO upgrading from EURO 4 to EURO 5. Figures 3 (b)&(c) show that NO and NO_2 emissions decrease consistently with EURO class for petrol cars, while they initially increased (to approximately EURO 2 for NO and EURO4 for NO_2, respectively) for diesel vehicles. Trends for taxis were not as pronounced as those seen for other vehicle types. Figures 3 (b)-(d) show relative high NO, NO_2, and NO_x emissions for EURO 1 and EURO 5 taxis and no obvious trend, although EURO 6 taxis have notably highest NO_2 and NO_x emissions among the LDVs fleet. Taxis have relatively larger emissions than the other LDVs, which could directly link to the drawbacks of accumulated mileage factor (36). For the buses, a similar interesting trend is observed for all emissions, in which EURO 4 buses have noteworthy lower emissions than the EURO 3 and EURO 5 ones, although EURO 6 buses have smallest NO, NO_x, and PM emissions among the other buses. In terms of PM emission, Figure 3(e) shows a descending trend in almost all vehicles, except taxis and HGVs, in which EURO 6 vehicles have smallest PM emission among the others. For PM emission of taxis, EURO 3 taxis have the highest emission among the others. Van and HGV trends are generally downward but less obvious, most likely reflecting the smaller sample sizes.

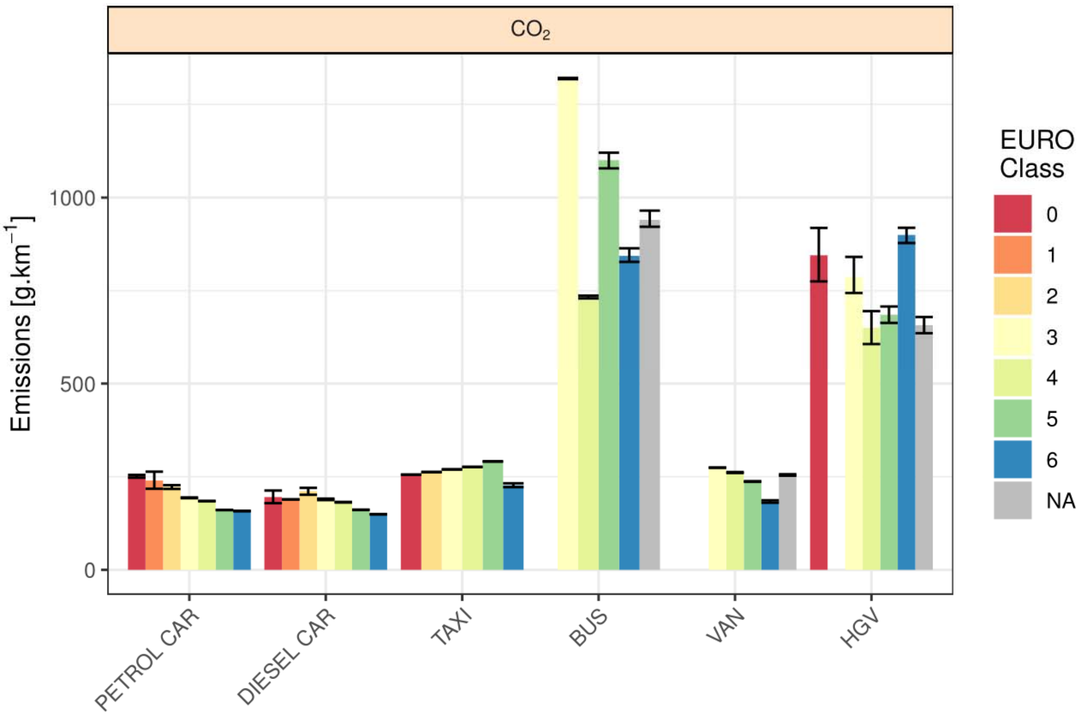
PM and NO_x emissions of heavy-duty diesel vehicles (HDDVs) are significant environmental challenges. The latest emission standards oblige HDDV manufacturers to develop new treatment and after-treatment technologies (see for example (37, 38)). Diesel particulate filters (DPFs) and selective catalytic reduction (SCR) technologies have been applied to mitigate tailpipe PM and NO_x emissions of HDDVs (39). DPFs catch the soot and other combustion particulate products by physical trapping with solid filters. Earlier HDDV DPFs used active filter regeneration technologies, increasing the temperature of the exhaust up to 500^{o}C to burn off the soot in the DPF, while the newer-to-market DPFs employed passive regeneration methods to remove collected PM from the filled DPFs (39, 40). In the later technologies, the exhaust temperature in the after-treatment device is raised to enhance engine-out conversion of NO to NO_2, and then NO_2 is used as the catalyst to oxidize stored PM.

The emission trends of HGVs and buses in Figure 3 reflects the development of HDDV treatment and after-treatment technologies. Figure 3(a) shows that EURO 6 (VI) HGVs have higher CO_2 emission factors than EURO 5 (V) and EURO 4 (IV) ones. Also, EURO 6 (VI) HGVs have higher and lower NO_2 and NO emission factors than EURO 5 (V) and EURO 4 (IV) ones, respectively. It seems that converting engine out NO to NO_2 and also oxidizing stored PM in the HDDV DPFs was more efficiently carried out in EURO 6 (VI) HGVs compared with the older EURO HGVs. The new technologies could significantly reduce HDDV tailpipe NO_x emission, while similar was not observed for the exhaust PM emission. Grigoratos et al. showed that the efficiency of the new HDDV treatment and after-treatment PM abatement technologies inversely correlate with vehicle speed, and higher PM emissions at lower speeds are most likely linked to lower exhaust system operating temperatures under these conditions (14). Hence, the observed drawback in tailpipe PM emission of EURO 6 (VI) HGVs could be attributed to the impairing of HGVs treatment efficiency in urban environments. For the buses, it seems that the recent technologies could control both NO_x and PM tailpipe emissions even in urban areas. However, the employed treatment technologies for reducing NO_x emission were more efficient than that for PM emission.

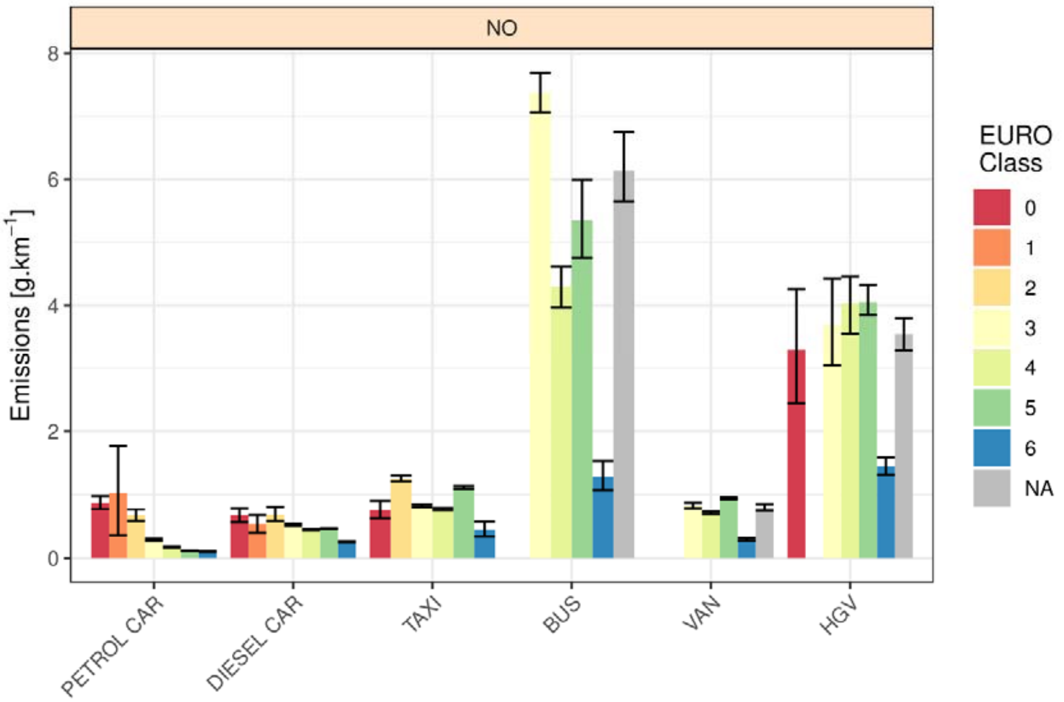
In terms of the most recent EURO upgrade, EURO 5 to EURO 6, the EDAR results suggest emissions (most notably NO and NO_x) are decreasing for most vehicle types, although there are some noteworthy exceptions. EURO 5 to EURO 6, taxi and possibly HGV NO_2 emissions increase, although the trend for the latter is less certain as indicated by relative size of error bars. EURO 5 to EURO 6, PM could be increasing for cars, vans and most notably HGVs although these are perhaps the most uncertain trends. Some of the highest emissions were observed for vehicles that do not appear to be registered in the vehicle information archives and of unknown EURO class. These were typically buses, vans and HGVs and labelled 'NA' in Figure 3.

The PEMS experiments of O'Driscoll et al. report 86-96% reductions in the NO_x emissions of petrol cars compared with the diesel ones (41), for comparison, in this paper 50-71% reduction is observed (see Figure 3(d)). Figure 3(d) shows that EDAR-reported NO_x emissions from EURO 6 diesel cars (0.52 g/km) were 2.7 times higher than that for petrol cars (0.19 g/km). However, O'Driscoll et al. observed that the tailpipe emission of NO_x in diesel light-duty vehicles, i.e. 0.44 g/km, was 11 times higher than for petrol ones (0.04 g/km) (41). Lower reported NO_x from petrol cars could reflect differences in the distributions of emissions from petrol and diesel cars and measurement techniques. PEMS provides an average emission across a longer journey while EDAR and other VERSSs provide a measure of vehicle-related emissions at the deployment site.

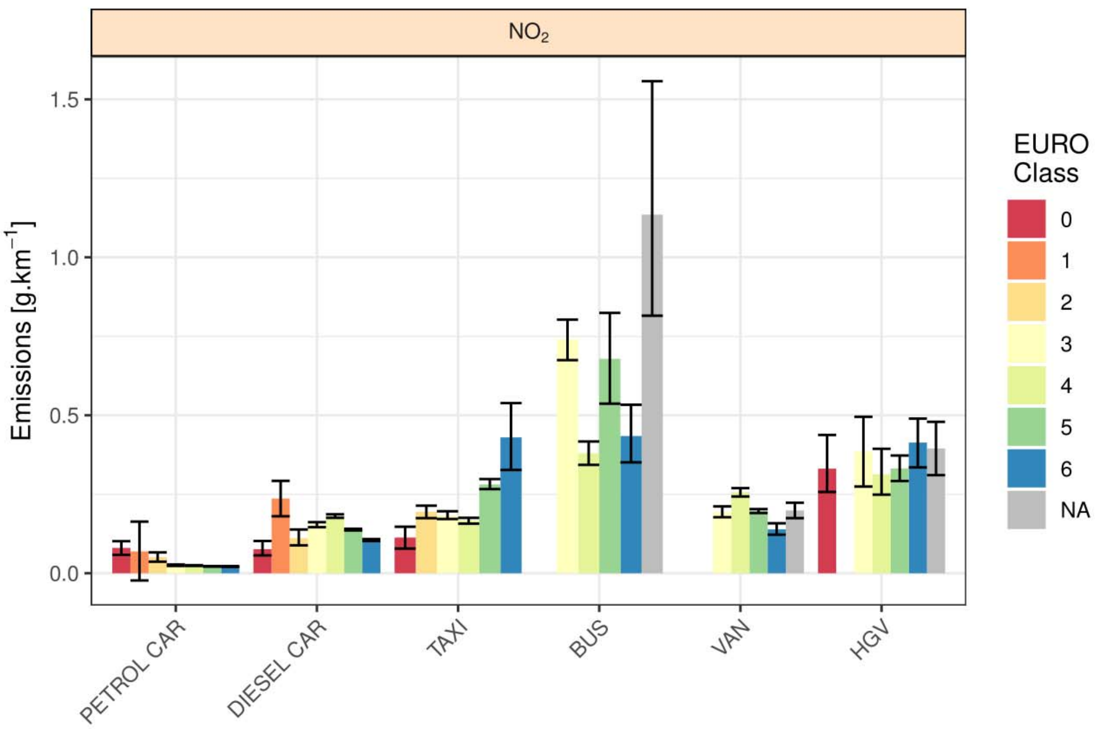
Figure 3 indicates an interesting trend in the on-road emission factors. While the study of Carslaw et al. for 2011 (23), a study using an across-road VERSS, reports little change in NO_x emissions from EURO 1 to EURO 4 cars, Figure 3 (d) presents a 32 to 42% reduction in the NO_x emission of cars form EURO 4 to EURO 6. Moreover, NO_x emission of HGVs and buses reduce 57% and 65% from EURO 4 to EURO 6, respectively, whereas Carslaw et al. report on relatively stable emissions from EURO 1 to EURO 4 (23).



(a)


NO
Emissions [g.km^{-1}]
0
2
4
6
8
PETROL CAR
DIESEL CAR
TAXI
BUS
VAN
HGV
EURO Class
0
1
2
3
4
5
6
NA

(b)


NO_2
Emissions [g.km^{-1}]
0.0
0.5
1.0
1.5
PETROL CAR
DIESEL CAR
TAXI
BUS
VAN
HGV
EURO Class
0
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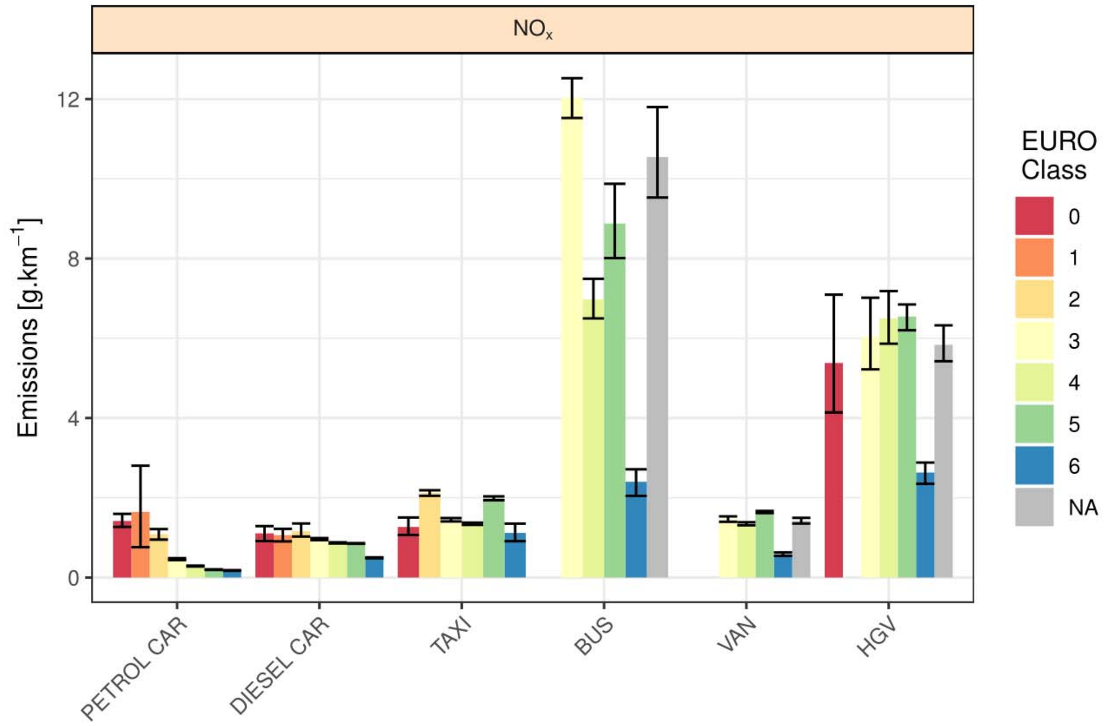
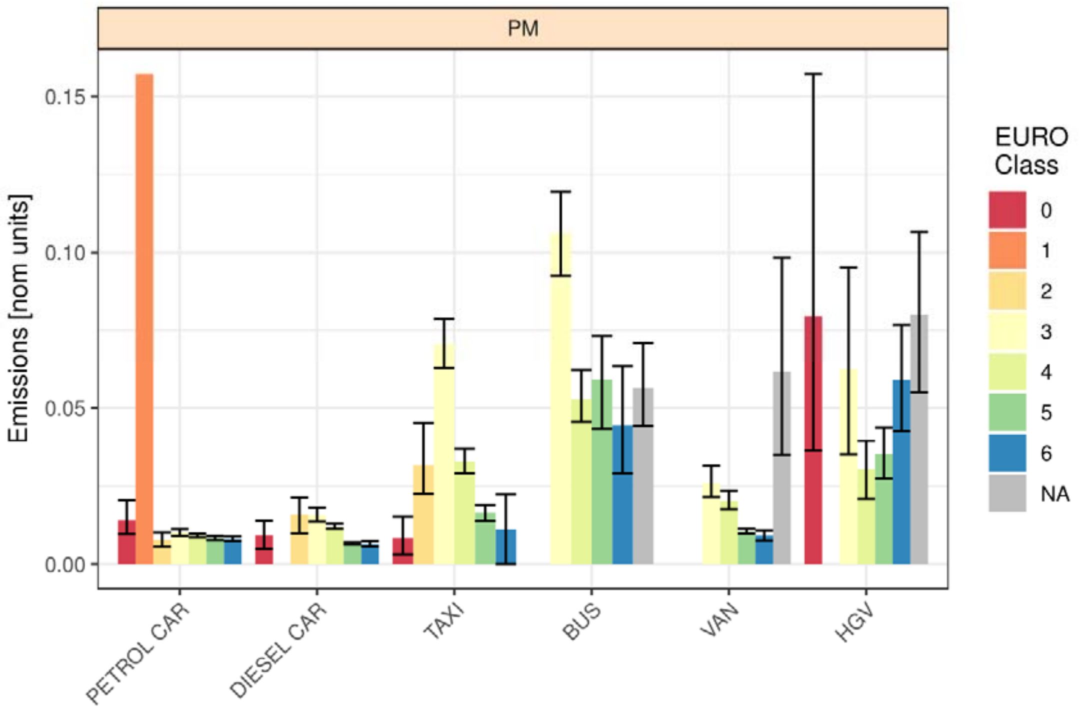
2
3
4
5
6
NA

(c)


NOx
Emissions [g.km−1]
12
8
4
0
PETROL CAR
DIESEL CAR
TAXI
BUS
VAN
HGV
EURO Class
0
1
2
3
4
5
6
NA

(d)


PM
Emissions [nom units]
0.15
0.10
0.05
0.00
PETROL CAR
DIESEL CAR
TAXI
BUS
VAN
HGV
EURO Class
0
1
2
3
4
5
6
NA

(e)

Figure 3. Average of (a) CO_2, (b) NO, (c) NO_2, (d) NO_x and (e) PM emissions from vehicles observed during the EDAR campaigns. Vehicles with unknown EURO classes were labelled 'NA' here.

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

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

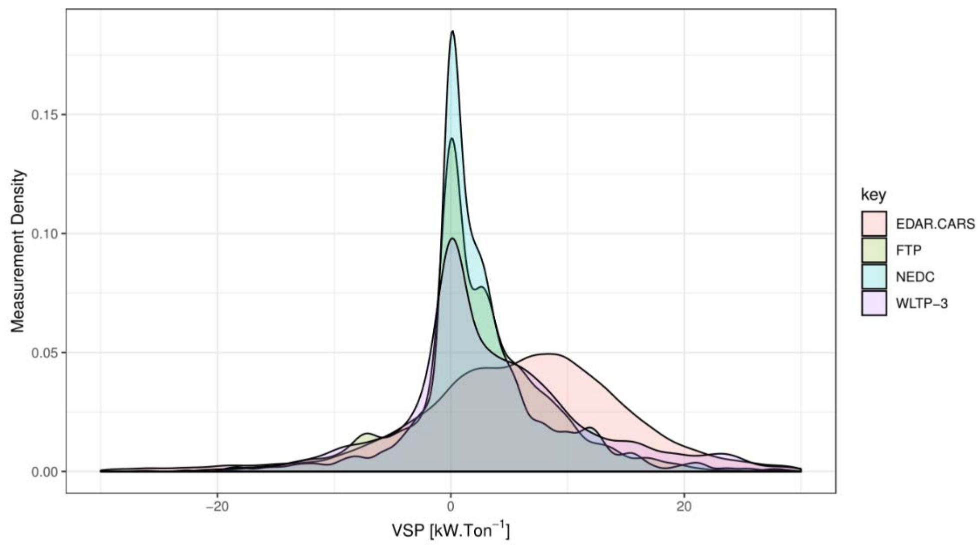


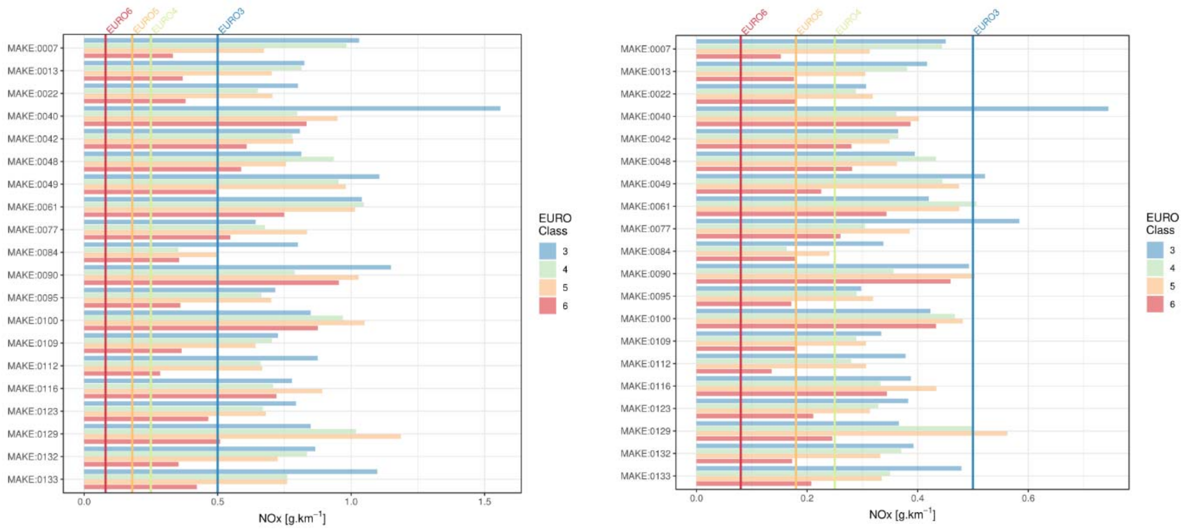
Figure 4. Comparison of vehicle specific power (VSP) distributions for EDAR data collected in the UK EDAR campaigns (this study) and VSP distributions for the other standard driving cycles including New European Driving Cycle (NEDC), Worldwide harmonised Light vehicles Test Procedure (WLTP) and Federal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

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

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

To address the first of these questions the diesel car subset of the EDAR data was reweighted, EURO 1 to EURO 5 to the NEDC VSP distribution and EURO 6 to the WLTP VSP distribution to provide a more direct basis for comparison. Figure 5 (a) shows the NO_x

emissions of diesel cars for selected makes and EURO classifications as determined by EDAR prior to reweighting. Here, all observed NO_x emissions are several times their associated emission standard, e.g. all shown EURO 6 diesel cars exceed the EURO 5 standard and several even exceed the EURO 3 standard. Based on the inspection of data in this fashion it would be easy to conclude that vehicles on-road are far worst emitters than in tests. However, if the data is reweighted according to the VSP distribution of the appropriate emission test drive cycle (as in Figure 5 (b)), corrected emissions are all much lower. For example, while none of the measured EURO6 diesel vehicles emitted less than the EURO 6 standard, most were less than EURO 5 standard, indicated much less pronounced differences.



(b)

(a)

Figure 5. Average NO_x (g/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 EUR0 3-5 and EURO 6 cars, respectively. Solid lines indicate associated EURO 3 to EURO 6 emissions standards.

There are however two related caveats: Firstly, this is probably still an over-estimation of NO_x emissions. The VSP distributions of the measurements are corrected but not the fuel consumption estimates used to calculate g/km NO_x. Doing that would likely increase the magnitude of the corrections for most vehicles. And, secondly, whatever correction strategy is applied, there is an assumption that any misalignment of emissions and (speed and acceleration based) VSP measurements is not introducing bias. With that in mind, VSP corrections should be viewed as indicative rather than quantitative unless such bias is addressed.

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

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

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

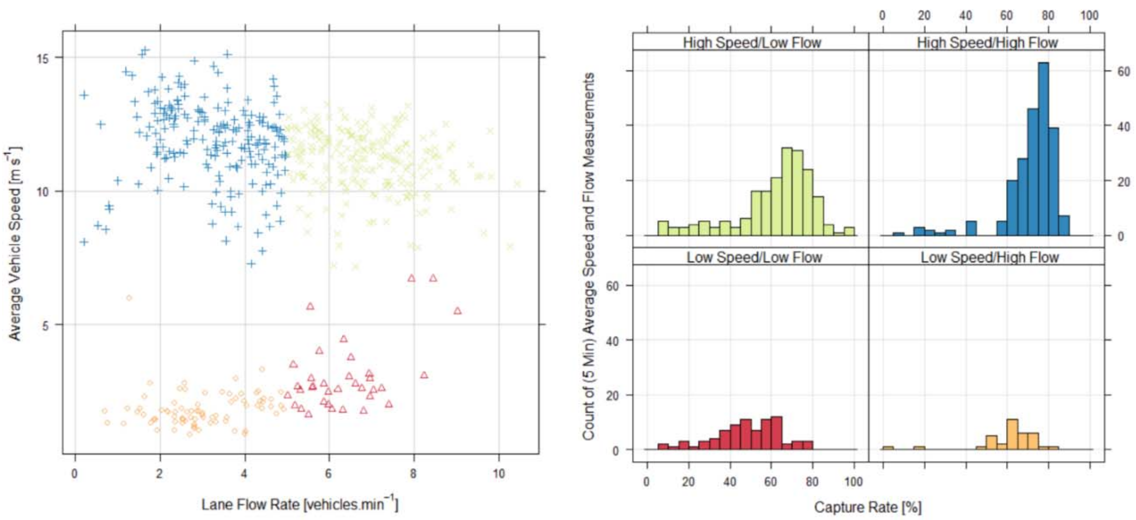


Figure 6. Example VERSS capture rates under different driving conditions.

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

During the last decade, three different zoned abatement strategies were considered in UK metropolitan areas to reduce the numbers of higher polluting vehicles entering designated areas. The first scheme implemented was the LEZ of London, which has covered most of Greater London for 24 hours a day, 7 days a week since February 2008, with the aim of reducing the exhaust gas emissions of diesel-powered commercial vehicles. Under the LEZ all the light-duty vehicles and motorcycles can freely enter the enforcement zone, but larger vans and minibuses that do not meet EURO 3 (or III) or later emission standards, and lorries, buses, and coaches that do not meet EURO 4 (or IV) or later emission standards are all charged to enter the enforcement zone.

The ULEZ was established in April 2019 to fuller reduce the number of worst polluting vehicles. Its stated aim is to achieve a 20% reduction in the vehicular emissions and drop the number of worst polluting vehicles from 35,600 to 23,000 (10). ULEZ is a more restricted scheme compared to the LEZ one, whereby motorcycles and petrol cars can freely enter the ULEZ areas if they meet or exceed EURO 3 and 4 standards, respectively. Diesel cars and vans, Buses, coaches and Lorries must meet or exceed EURO 6 standards. In addition to London, other metropolitan areas within the UK have been struggling with air pollution concerns, and so newer more restrictive schemes are now being implemented both in London and elsewhere. For example, the city of Birmingham within the West Midlands metropolitan area has a CAZ scheme due to be established in 2021. In addition to Birmingham, the cities of Leeds, Liverpool, Bristol, Bath and Southampton will also be introducing CAZs. CAZs are being set up in response to concentrations of NO_2 which exceeds the European Union limitations (45). The CAZ in Birmingham is due to be a 'type D' CAZ, which is designed principally based on the type of the fuel of vehicles, whereby all petrol and diesel vehicles should meet or exceed EURO 4 and 6 emission standards to freely enter the CAZ area, respectively. Whilst all vehicles should meet the EURO standards, certain vehicles are excluded from the scheme. Motorcycles are currently completely free to enter the CAZ enforcement area without any restrictions.

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

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

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

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

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

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

Scheme / Pollutant	LEZ	ULEZ	CAZ
NO_x	7.4	32.8	36.5
PM	2.3	17.9	14.5
CO_2	0.2	10.3	7.6

It indicates that the LEZ has the smallest EUP factors compared to the two other types of low emissions zone. This is expected because the LEZ was the earliest and least restrictive of these strategies. The CAZ type 'D' emissions zone could reduce more than 30%, 14% and 8% of the NO_x, PM and CO_2 vehicular emission factors, respectively. The ULEZ is expected to have a better performance by comparison with the others for CO_2 and PM, but the type 'D' CAZ is expected to provide the largest NO_x reductions.

5. Conclusions

In this study data collected in five EDAR deployments in the UK, in 2016 and 2017, were analysed. Subset according to vehicle type, fuel type and EURO class, the findings provide valuable evidence on UK vehicle fleet emissions. In terms of emission trends, it is observed that NO and NO_x vehicle emissions are typically very similar or more often better for the main vehicle types for EURO 6 vehicles by comparison to their EURO 5 counterparts, which is obviously an encouraging finding given trends EURO 3 to 5. However, some increases were observed for NO_2 EURO 5 to EURO 6 for (diesel) Taxis and possibly HGVs, and perhaps most concerningly an increase in PM emissions EURO 5 to EURO 6 for HGVs. Also noteworthy was the observation that unknown vans, buses and HGVs, those for which there was little or no information in public archives, were often the dirtiest vehicles in their classes, suggesting that where counts of such vehicles are high they could be making a significant local contribution to emissions.

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

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

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