



Remote sensing of motor vehicle emissions in London

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THE TRUE INITIATIVE

Studies have documented significant and growing discrepancies between the amount of nitrogen oxides (NO_x) emissions measured in diesel vehicle exhaust during type-approval tests and the amount that the vehicle emits in “real-world” operation—on the road, in normal driving. Excess real-world emissions are an important issue, particularly in Europe where dieselization of the light-duty vehicle fleet is much higher than in other global regions. Poor real-world NO_x emission control has contributed to persistent air quality problems in many European cities and has adversely impacted public health.

FIA Foundation, the International Council on Clean Transportation (ICCT), C40 Cities, Global NCAP, and Transport and Environment have established The Real Urban Emissions (TRUE) Initiative. The TRUE initiative seeks to supply cities with data regarding the real-world emissions of their vehicle fleets and equip them with technical information that can be used for strategic decision making. TRUE will use a combination of measurement techniques to produce a granular picture of the on-road emissions of the entire vehicle fleet by make, model, and model year.

TRUE has commissioned two pilot studies to measure real-world emissions from vehicle fleets in European cities using remote sensing technologies. This paper presents results from the first pilot study, which was carried out in London in the winter of 2017–2018.

EXECUTIVE SUMMARY

In March 2017, London's Mayor, Sadiq Khan, announced that the city would be collaborating with the TRUE initiative. The purpose of the collaboration was to increase the availability and accessibility of information on real-world vehicle emissions in the city. The TRUE initiative committed to taking real-world emission measurements in London and sharing the data publicly. The data would be used for a number of different applications including consumer information, evaluating the effectiveness of implemented policies, and informing new policies. This report summarizes the result of this effort.

From November 2017 through February 2018, remote sensing was conducted at nine locations across Greater London. During this time, more than 100,000 emissions records from individual vehicles were collected. Data were collected on passenger cars, light commercial vehicles, taxis, buses, trucks, and motorcycles. Data also were collected over a range of ambient temperatures and driving conditions. The data were compiled with other existing data collected in other European cities and analyzed using methodologies developed previously.

The analysis conducted shows the following:

- Nitrogen oxides (NO_x) emissions from diesel cars in London are, on average, 6 times as high as those from petrol cars when expressed on a per kilometer basis. NO_x emissions from petrol passenger cars have declined with tightening emission standards, and Euro 5 and Euro 6 averages are within 1.3 times the petrol emission limits. Average NO_x emissions from Euro 5 and 6 diesel cars, however, are approximately 5-6 times their respective laboratory emission limits. The average emissions from passenger vehicles and light commercial vehicles being used in London do not differ extensively from those in the rest of Europe.
- Carbon monoxide (CO) emissions from passenger cars are significantly lower for newer vehicles and CO emissions for diesels are, on average, lower than those of petrol vehicles. Average CO emissions from petrol cars appear to increase as a vehicle ages and this increase is more pronounced for a small subsection of the fleet.

- Particulate matter (PM) emissions from passenger cars are low for new diesel and petrol cars. Diesel cars, Euro 5 and newer, come equipped with diesel particulate filters and demonstrate significantly lower PM emissions than older vehicles without filters.
- Diesel London Taxi Company black taxi TX models produce, on average, higher NO_x emissions than diesel passenger cars covered by the same emissions standard. Notably, NO_x emissions from Euro 5 taxis are greater than those from taxis certified to previous Euro standards and approximately 3 times as high as emissions from Euro 5 diesel cars. These results align with laboratory testing conducted by Transport for London.
- Buses in London have experienced a significant reduction in average NO_x emissions over the past 5 years. When expressed in units of grams per kilogram of fuel burned, NO_x emissions from buses sampled in this study were 65% lower than those from buses sampled in similar studies conducted in 2012 and 2013. A similar comparison for other vehicle types shows that, over the same time frame, average emissions from the diesel passenger car and light commercial vehicle fleet have decreased by 22% and 15%, respectively, while average NO_x emissions from the taxi fleet have not improved (see Figure ES1).
- Euro 5 and earlier diesel cars are estimated to be responsible for more than 60% of the NO_x emissions from passenger cars in Greater London. This is the group of vehicles that will be excluded from central London as part of the upcoming Ultra Low Emission Zone.

The results presented here give some insights into the real-world emissions of London's current fleet. While average vehicle emissions have decreased in recent years, a large proportion of high emitting vehicles are still on the road around the city. These results also help to evaluate the effectiveness of implemented policies. For example, policies put in place to reduce NO_x emissions from the bus fleet have been quite effective over the past 5 years. And finally, the results can be used to predict the impact of future policies. For example, the results of the analysis indicate that the upcoming Ultra Low Emission Zone will have a significant impact in reducing NO_x emissions in central London.

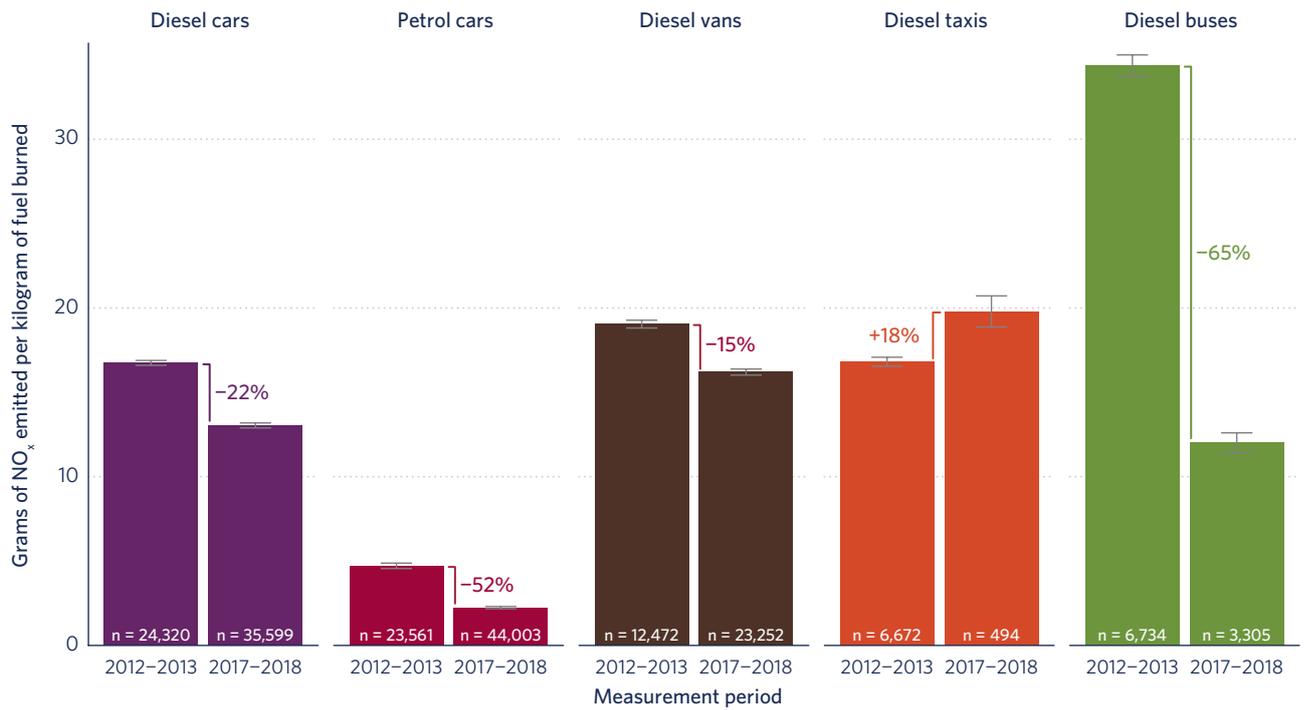


Figure ES1. Average fuel-specific NO_x emissions by vehicle group, measured in London in 2012-2013 and 2017-2018.
 Notes: The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean.

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ABBREVIATIONS

CO	carbon monoxide
CO₂	carbon dioxide
DVLA	Driver and Vehicle Licensing Agency
g/kg	grams per kilogram fuel
g/km	grams per kilometer
HC	hydrocarbons
ICCT	International Council on Clean Transportation
LEZ	Low Emission Zone
MVRIS	Motor Vehicle Registration Information System
NEDC	New European Driving Cycle
NH₃	ammonia
NO	nitric oxide
NO₂	nitrogen dioxide
NO_x	nitrogen oxides
Opus RSE	Opus Remote Sensing Europe
PEMS	portable emissions measurement system
PM	particulate matter
RDE	Real Driving Emissions
RSD	remote sensing device
SMMT	Society of Motor Manufacturers and Traders
TfL	Transport for London
TRUE	The Real Urban Emissions Initiative
ULEZ	Ultra Low Emission Zone
VSP	vehicle specific power
ZEC	zero emissions capable

INTRODUCTION

At the March 2017 Air'volution event organized by C40 Cities, the Mayor of Paris, Anne Hidalgo, and Mayor of London, Sadiq Khan, jointly announced their intention to make real-world emissions data on vehicles operating in their cities available to the public in order to help consumers make better informed choices about the environmental impact of the cars they drive and to support initiatives to reduce the harmful impacts of air pollution.¹ To support these efforts, the TRUE initiative has commissioned real-world vehicle emissions measurement studies in the cities of London and Paris.

The TRUE studies address growing concerns regarding elevated emissions from in-use vehicles, in particular diesel cars and light commercial vehicles, through independent measurements of emissions from large numbers of vehicles operating in real-world conditions. The data gathered in these pilot studies will help local authorities to better understand the role motor vehicles play in urban air quality problems and to develop evidence-based policies to control emissions and protect public health. Combined with data collected in similar studies, the results from these campaigns also will contribute to a growing vehicle emissions database, which forms the basis of the TRUE real-world passenger vehicle emissions rating scheme.

This report presents results from the first of the TRUE real-world vehicle emissions measurement studies, which was carried out in London in the 2017–2018 winter. The study used remote sensing technology to measure emissions from more than 100,000 vehicles operating on the streets of London. Remote sensing technology is capable of sampling emissions from a large number of vehicles in a relatively short period of time, and as such, was well suited to the goals of this project.

The report provides a brief overview of the remote sensing sampling campaign and presents initial results from the analysis of data collected during the study. Emissions results presented here focus primarily on light-duty vehicles. Results are presented for analysis of data collected during the 2017–2018 London sampling, as well as for a larger database of remote sensing data for European vehicles to which the London data have

been added. Additional case studies were carried out to investigate emissions from specific vehicle fleets—black London Taxi Company TX taxis and transit buses—and to evaluate high-emitting vehicle groups.

TRUE LONDON REMOTE SENSING STUDY OVERVIEW

The TRUE London remote sensing study was carried out in the winter of 2017–2018. The core study consisted of measurements of vehicle emissions at multiple locations throughout Greater London beginning in November 2017 and continuing through February 2018. Four additional days of sampling were conducted at a single location in April 2018 to evaluate remote sensing instrument technologies and supplement the data collected during the core measurement campaign.

The emissions study was led by Opus Remote Sensing Europe (Opus RSE), a leading provider of remote sensing technology and services, and Ricardo, an engineering and environmental consultancy with expertise in vehicle emissions measurement. Data also were collected by the University of York using the University of Denver FEAT instrument. Additional support and assistance, in particular during the planning and permitting phases of the study, was provided by the Greater London Authority, Transport for London, and TRUE initiative partners.

This section provides a brief overview of the data collection phase of the TRUE London study, including details of project objectives, remote sensing instrumentation, sampling locations, and a summary of the quantity of data obtained during the study. A more detailed discussion of the field campaign and methodologies applied for data collection and processing is available in a companion publication prepared by Opus RSE.²

OBJECTIVES

The high-level objective of the TRUE London remote sensing study was to provide a robust picture of real-world emissions from the current fleet of light-duty vehicles—passenger cars and light commercial vehicles—operating in London. Remote sensing was

1 "Mayors of Paris and London Announce Car Scoring System to Slash Air Pollution on City Streets," C40 Cities, March 29, 2017, https://www.c40.org/blog_posts/mayors-of-paris-and-london-announce-car-scoring-system-to-slash-air-pollution-on-city-streets

2 Opus RSE, "TRUE - The Real Urban Emissions Initiative London 2017-2018: Fieldwork and methodology report," 10 July, 2018.



Figure 1. RSD5000 remote sensing deployed at the Greenford Road sampling site in the Borough of Ealing.

selected as the measurement technique for this study because of the very high sample sizes that can be obtained using this technology relative to other real-world vehicle emissions measurement methods.

At the outset of the project, a target of 100,000 individual vehicle emissions measurements was set, which heavily influenced the length of the field sampling campaign. Further emphasis was placed on increasing the diversity of the sampled vehicle population and range of observed vehicle operating conditions by sampling at multiple locations with varying physical and traffic characteristics. Together, larger sample sizes and greater diversity in sampling conditions serve to extend the types of analyses which can be done with remote sensing data and enhance the statistical power of results and conclusions drawn from such analyses.³

While not the primary focus of the study, remote sensing technology is capable of measuring emissions from other vehicle types in addition to light-duty vehicles.

These include urban transit buses, heavy trucks, and motorcycles. The extent to which useful emissions data were obtained for these vehicle types during the TRUE London study will be discussed in following sections.

REMOTE SENSING INSTRUMENTATION

The primary remote sensing device (RSD) used in the London study was the Opus AccuScan RSD5000 (henceforth RSD5000). Figure 1 shows the RSD5000 system deployed and collecting data at the Greenford Road sampling site in the Borough of Ealing. A full description of the RSD5000 can be found in the Opus RSE fieldwork and methodology report. Recent publications from the ICCT and the TRUE initiative also provide a more in-depth discussion of remote sensing technologies.^{4,5}

Briefly, the RSD5000 consists of three coordinated units:

- The first unit measures vehicle emissions by absorption spectroscopy. Infrared and ultraviolet

³ Jens Borken-Kleefeld and Tim Dallmann, *Remote sensing of motor vehicle exhaust emissions*, (ICCT: Washington, DC, February 2018), https://www.theicct.org/sites/default/files/publications/Remote-sensing-emissions_ICCT-White-Paper_01022018_vF_rev.pdf

⁴ Ibid.

⁵ Yoann Bernard, Uwe Tietge, John German, Rachel Muncrief, *Determination of Real-World Emissions from Passenger Vehicles Using Remote Sensing Data*, (ICCT: Washington, DC, June 5, 2018), <https://www.theicct.org/publications/real-world-emissions-using-remote-sensing-data>

light beams are passed through the exhaust plume of a vehicle. The attenuation of these beams as they pass through the vehicle's exhaust plume and ambient air provides a measure of the incremental concentrations above the background level of various pollutants of interest. The RSD5000 used in the TRUE London study measures nitrogen monoxide (NO), nitrogen dioxide (NO₂), carbon monoxide (CO), carbon dioxide (CO₂), hydrocarbons (HC), and ammonia (NH₃). Opacity is measured as a proxy for particulate matter (PM). Each individual vehicle exhaust plume measurement lasts for 0.5 seconds. The RSD5000 has a 200 Hz sampling rate, which means 100 distinct measurements of the vehicle's exhaust plume are made during the 0.5 second sampling interval.

- The second unit measures speed and acceleration of the vehicle just prior to the emissions measurement. Speed and acceleration provide a measure of the vehicle's engine load, conventionally expressed as vehicle specific power (VSP). This load is associated with the instantaneous emission rate.
- The third unit, a camera, takes a picture of the vehicle's license plate, which is used to acquire vehicle technical information from registration databases.

A system control unit coordinates the operation of the emissions analyzer, speed and acceleration sensors, and camera, gathering and integrating readings from each of these units. Emissions readings, vehicle operating conditions, and ambient conditions are reported in real time. Vehicle technical information is retrieved later from registration databases. In this study, two databases were accessed for this purpose—the Driver and Vehicle Licensing Agency Database (DVLA) and the Society of Motor Manufacturers and Traders (SMMT) Motor Vehicle Registration Information System (MVRIS).

A complete remote sensing record for an individual vehicle contains the following information:

- the concentration measurement of each emission species relative to CO₂ above the concentration in ambient air;
- the vehicle's speed and acceleration;
- the measurement conditions: road grade, ambient temperature and pressure, and relative humidity;
- the vehicle's technical information, including brand, model, category, model year, body type and size,

fuel type, engine size, Euro standard, type-approval CO₂ value, and empty vehicle mass.

During the London study, a second remote sensing device, the FEAT from the University of Denver,⁶ was used in addition to the RSD5000 during a portion of the field campaign. The instruments share the same measurement principle, with the RSD5000 being the commercial version of the FEAT system. The FEAT measures the same suite of pollutants as the RSD5000 and offers improved NO₂ measurement capabilities, which Opus intends to include in future versions of the RSD5000 instrument. In London, the FEAT was used primarily for targeted experiments and not for core data collection. As such, all results presented henceforth are representative of data from the RSD5000 instrument only, unless otherwise noted.

SAMPLING SITES AND SCHEDULE

The RSD5000 was used to measure vehicle emissions at nine sites throughout Greater London during the data collection phase of the study. The location of each site is displayed in Figure 2. Opus RSE and Ricardo carried out a preliminary assessment of potential sampling locations during the planning stages of the project, with an emphasis on identifying sites with the following characteristics:

- Single lane roads to prevent interference from non-target vehicle exhaust plumes
- Steady traffic flow to provide sufficient sampling rates and to avoid sampling disruptions during periods of congestion
- Slight upward slope or locations where vehicles are under acceleration in order to provide engine load
- Sufficient distance from residential areas to limit measurements of cold engines
- Adequate space to set up instrumentation and ensure operator safety without disrupting traffic flows

A total of 16 potential sampling sites were identified, with nine selected for use during the field data collection campaign.

The core data collection phase of the study began November 6, 2017 and ended February 16, 2018. Sampling during winter months provided an

⁶ "Fuel Efficiency Automobile Test Data Center," University of Denver, accessed October 23, 2018, <http://www.feabiochem.du.edu/>

London sampling sites

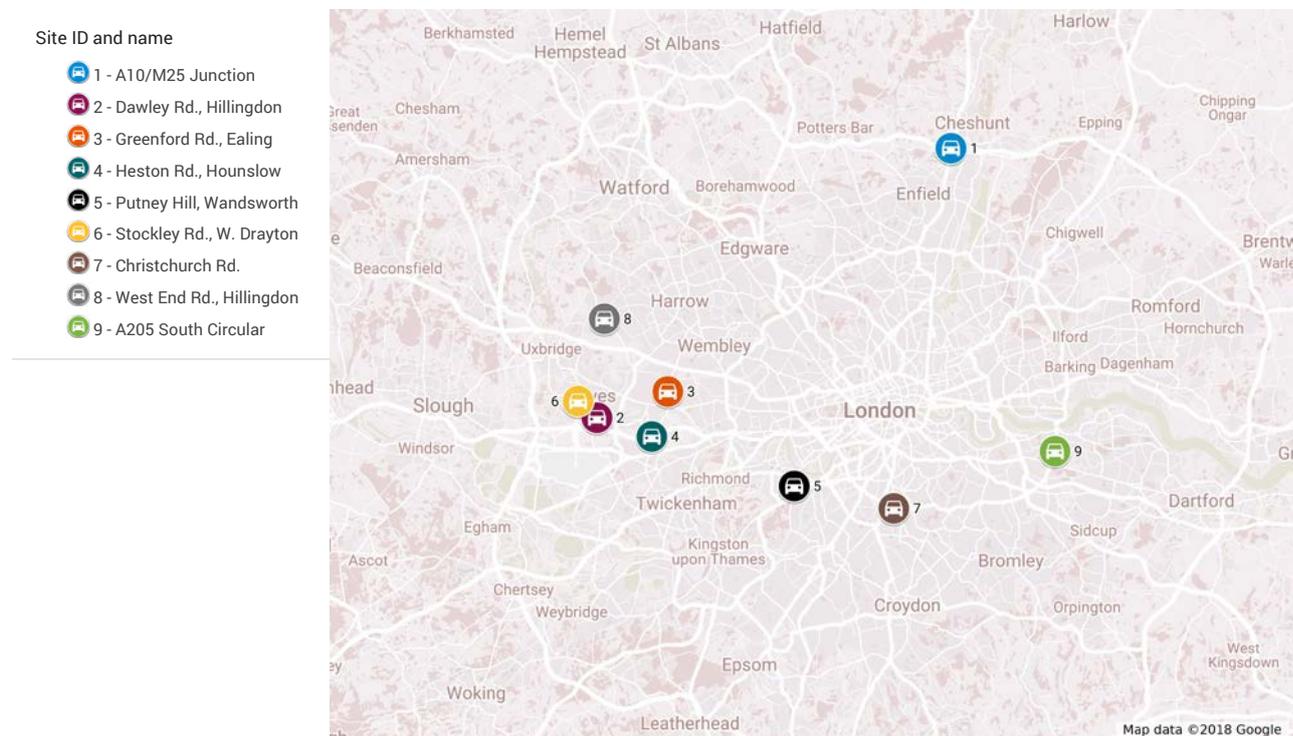


Figure 2. Measurement locations for the TRUE London 2017–2018 remote sensing study.⁷

opportunity to measure emissions from vehicles operating in lower ambient temperatures than is typical of existing European remote sensing data, most of which has been collected during seasons with more favorable weather conditions.

During the data collection period, vehicle emission measurements were made on a total of 41 days. Sampling was not conducted on weekend days or during the holiday period. Some delays to the sampling schedule were experienced due to downtime for equipment repair and inclement weather.

Additional testing was performed over four days in April 2018 at the Putney Hill site. The primary purpose of this testing was to investigate the relative performance of the RSD5000 and FEAT instruments.

DATA COLLECTION SUMMARY

Table 1 provides an overview of the core data collection phase of the London remote sensing study, including the total time spent sampling and number of measurements made at each site and summed over the entire sampling

period. Note that data collected over four days of sampling in April 2018 are not included in the table. The number of remote sensing records is presented for three cases:

- *Number total records* shows the number of attempted individual vehicle remote sensing emissions tests.
- *Number valid records* gives the number of attempted measurements that met predefined quality criteria and were deemed to be successful. Sometimes, for example when there is a poor exhaust plume signal or interference from other vehicles on the road, an attempted emissions test may not be successful. In these cases, the exhaust measurement does not meet certain quality criteria and the record is marked as invalid. These records do not provide useful information about the emissions of a tested vehicle and are thus not considered in the analysis of the collected data. During the London study, 18% of attempted emissions measurements did not yield valid emissions data.
- *Number complete records* shows the number of vehicle remote sensing tests that yielded valid emissions data and for which technical information about the test vehicle was available. Meaningful analysis of remote sensing data requires information about the

⁷ Additional details of the sampling sites can be found in the Opus RSE fieldwork and methodology report.

Table 1. Overview of the data collection phase of the TRUE London remote sensing study.

Site ID	Site name	Road type	Measurement days	Total sampling time (hr)	Number total records	Number valid records	Number complete records
1	A10/M25 Junction	Motorway junction	7	43.4	31,391	23,314	19,834
2	Dawley Rd., Hillingdon	Roundabout	1	3.2	1,695	1,148	1,015
3	Greenford Rd., Ealing	Urban road	4	29.7	12,178	9,337	8,287
4	Heston Rd., Hounslow	Urban road	2	6.1	1,999	1,439	1,327
5	Putney Hill, Wandsworth	Urban road	8	49.8	34,304	31,153	29,234
6	Stockley Rd., West Drayton	Motorway access	1	7.4	1,166	1,023	930
7	Christchurch Rd.	Urban road	6	40.0	18,895	16,251	14,863
8	West End Rd., Hillingdon	Urban road	9	64.5	28,956	23,621	22,120
9	A205 South Circular	Urban Road	3	13.3	6,608	5,851	5,196
Total			41	257	137,192	113,137	102,806

characteristics of the vehicles that are tested. These data are retrieved by matching recorded license plate numbers to records in registration databases. If the license plate of the test vehicle is not accurately recorded and transcribed or if the transcribed plate number cannot be matched to the registration database, the vehicle's information cannot be retrieved. Of the 113,137 valid remote sensing records, technical data were available for 102,806, or 91%, of the tested vehicles. This set of 102,806 complete remote sensing records forms the basis for the analysis that is presented in this paper.

Over the course of 41 days of sampling, data were collected for a total of 257 hours, yielding 113,137 valid emissions measurements. This works out to a study average of about 440 valid records per hour of sampling. The four sampling sites visited most often produced 83% of valid emissions records. Conditions at these sites were favorable for data collection and they were therefore prioritized by the remote sensing operators. Of the nine sites visited during the London study, six produced more than 5,000 valid emissions records each. Two of the three remaining sites—Dawley Road and Stockley Road—were deemed to be of poor quality due to traffic congestion or low traffic flows, and measurements were made on only one or two days at each location. The remaining site, Heston Road, was used primarily as

a backup during periods of rain because of its location underneath a bridge.

DATA PROCESSING AND ANALYSIS

A complete database of London remote sensing records was provided by Opus RSE at the completion of the data collection phase of the study. These data were incorporated into the CONOX remote sensing database, which is a collection of remote sensing data collected in European cities.⁸ With the addition of the London 2017–2018 data, the CONOX database now includes close to 1 million records and more than 600,000 valid light-duty vehicle measurements.

Post-processing and statistical analyses of the London dataset followed methods presented in Bernard et al.⁹ The following sections detail the results of these analyses, beginning with an overview of the characteristics of the fleet of vehicles whose emissions were measured

8 Åke Sjödin et al., "Real-driving emissions from diesel passenger cars measured by remote sensing and as compared with PEMS and chassis dynamometer measurements—CONOX Task 2 report" (Federal Office for the Environment, Switzerland, May 2018), <https://www.ivl.se/download/18.2aa26978160972788071cd79/1529407789751/real-driving-emissions-from-diesel-passenger-cars-measured-by-remote-sensing-and-as-compared-with-pems-and-chassis-dynamometer-measurements-conox-task-2-r.pdf>

9 Bernard et al., *Determination of Real-World Emissions*.

during the London remote sensing study. Following this discussion, emissions results for passenger vehicles and light commercial vehicles are presented. These vehicle types were the primary focus of the study, and account for most of the remote sensing data collected during the sampling campaign. Results are presented for NO_x, CO, and PM emissions, with detailed assessment of how emissions vary by specific vehicle attributes, such as fuel type, Euro standard, and vehicle age. Results from the winter 2017–2018 testing are further compared to remote sensing data collected in other European cities.

Remote sensing results for specific fleets are considered in case studies of emissions from taxis and urban transit buses. Finally, emissions data are combined with information on the prevalence of specific vehicle types in the London dataset in order to investigate high-emitting vehicle groups.

CHARACTERISTICS OF THE SAMPLED FLEET

Figure 3 presents an overview of the characteristics of the vehicle fleet sampled during the TRUE London remote sensing study. These data include only the 102,806 complete records, where both valid emissions and vehicle technical information were available. Light-duty vehicles were the focus of this study, and thus represent the vast majority of the dataset. Passenger cars and light commercial vehicles account for 71% and 21% of all records, respectively. Although sample sizes for other vehicle types were smaller, a considerable amount of data was also collected for heavy goods vehicles (2,944 records), buses (2,332), and motorcycles (867). Two percent of total records were for other vehicle types or could not be assigned to a specific vehicle class.

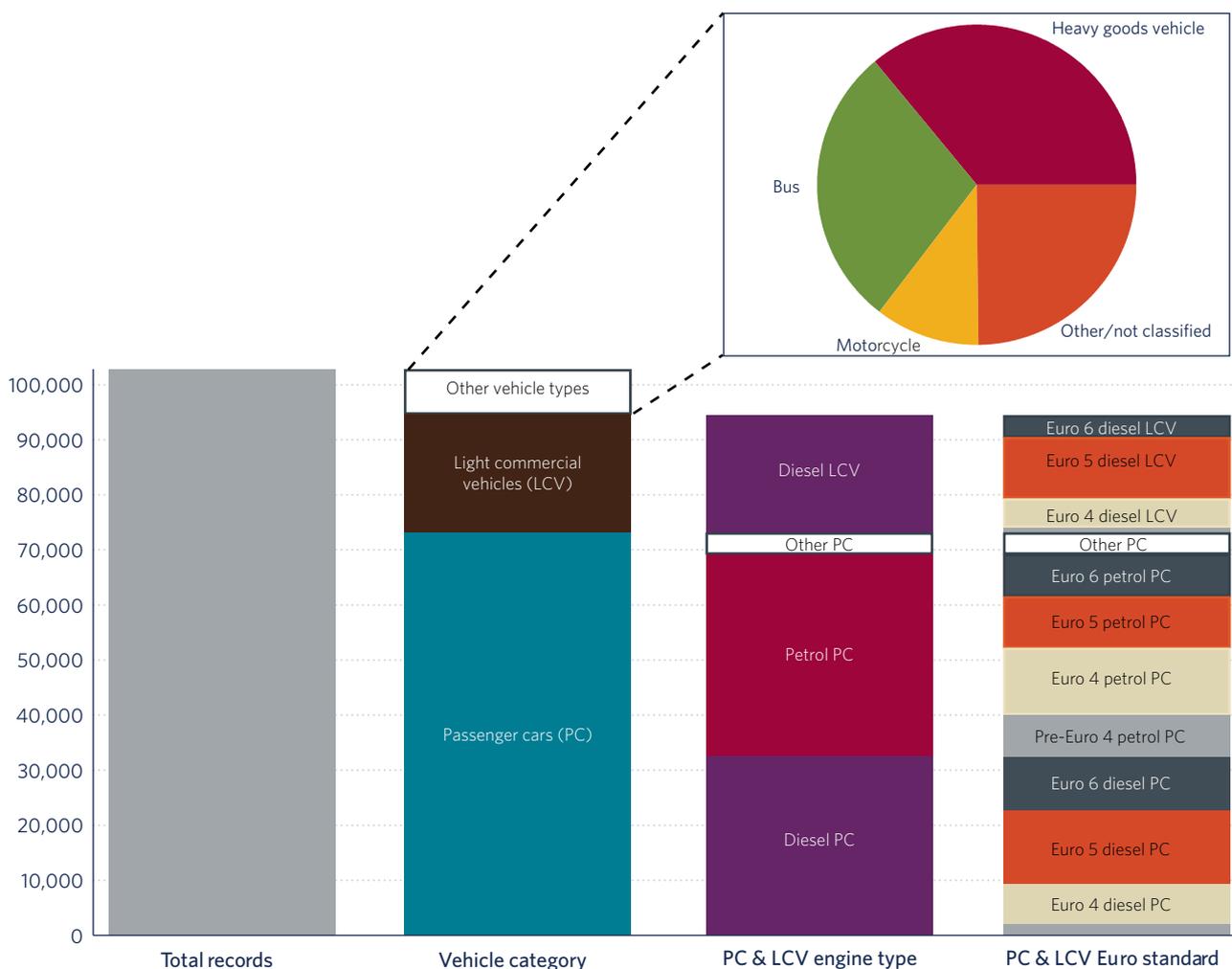


Figure 3. Characteristics of the vehicle fleet sampled in the TRUE London remote sensing study. Notes: Total number of complete records are shown by vehicle type and, for passenger cars and light commercial vehicles, by engine type and Euro standard. The inset pie chart shows the relative proportion of non-light-duty vehicle types in the dataset.

The third bar in Figure 3 shows the light-duty vehicle sample broken down by engine type. Passenger cars are about evenly split between diesel and petrol engines, with slightly more records for petrol cars. Other passenger car types, mostly hybrids, accounted for approximately 4,000 records. Virtually all of the light commercial vehicles in the London dataset were powered by diesel engines.

Further disaggregation of the light-duty vehicle sample by emission standard shows Euro 4 was the most common emission standard for petrol passenger cars (33% of petrol passenger car sample), whereas for diesel passenger cars, vehicles certified to Euro 5 standards were most prevalent (41% of diesel passenger car sample). Euro 6 certified vehicles represented 21% and 30% of the petrol and diesel passenger car data, respectively. As was the case for diesel passenger cars, Euro 5 was also the most common emission standard for diesel light commercial vehicles, accounting for more than 50% of total records for this vehicle type.

Table 2 summarizes testing conditions and passenger car fleet characteristics in the 2017–2018 London measurements and the rest of the CONOX remote sensing data. The table groups the data by fuel types and emission standards to facilitate comparison within and across sub-samples of the data.

The second, third, and fourth columns of Table 2 present, respectively, the number of measurements, the average vehicle age at the time of measurement, and the average road grade at the measurement sites. The next three columns plot certified CO₂ emission values over the New European Driving Cycle (NEDC), ambient temperature at the time of measurement, and the power demand in terms of VSP. Median values for London and the rest of the CONOX data are presented in each graph. Lastly, the rightmost column includes contour plots of vehicle acceleration over vehicle speed for London and CONOX data. The vehicle acceleration values presented here include gravitational forces from uphill driving to allow for better comparisons across datasets.

The passenger car fleet in the 2017–2018 London data stands out in a number of ways compared with

other CONOX data. Because the CONOX data were collected from 2011 to 2018, the recent London campaign includes a significantly higher share of Euro 6 vehicles, whereas older emission standards, Euro 2 through Euro 4, are less prevalent in the London data. Because the London measurements are more recent than the bulk of the CONOX measurements, vehicles of a given Euro standard were also marginally older at the time of measurement. Lastly, the newer London fleet had lower certified CO₂ emissions than other CONOX data, partly because newer vehicles have lower average CO₂ emission values due to EU CO₂ standards, and partly because remote sensing campaigns in the Canton of Zurich, Switzerland—a vehicle market with comparatively large, powerful vehicles—had a disproportional impact on the average CO₂ emission values in the CONOX data.

The 2017–2018 London data also stand out from the rest of the CONOX data in terms of measurement conditions. The average road grade in London was consistently lower than in other CONOX data, largely due to the comparatively steep road grade (9%) in the abundant Zurich remote sensing data. The lower road grade and lower average speeds (see rightmost column) in the London data also led to lower power demand on vehicles, with median VSP values around 6 kW/t compared with 12 kW/t in the CONOX data. Lastly, the median ambient temperature in London was approximately 10 °C lower than elsewhere because London data were collected in the winter of 2017–2018, whereas the vast majority of other remote sensing measurements were conducted in summer months.

Taken together, the 2017–2018 remote sensing measurements conducted in London broaden the range of testing conditions of the CONOX dataset, particularly with respect to low ambient temperature, and add more data on modern vehicles. Differences in fleet characteristics between 2017–2018 London data and the rest of the CONOX dataset are consistent with vehicle market developments. While the London sample stands out with comparatively low ambient temperatures, the range of temperatures remains well within normal conditions in the European climate, and other measures of driving conditions are milder than in other CONOX data.

Table 2. Summary of remote sensing testing conditions and passenger car fleet characteristics in London (blue) and the rest of the CONOX database (brown).

Euro standard/ Fuel	Measurements	Avg. vehicle age (years)	Avg. road grade	CO ₂ value (g/km, NEDC)	Ambient temperature (°C)	VSP (kW/ton)	Acceleration (km/h/s) over speed (km/h)
Euro 2 Diesel	66 3,922	19 17	2% 4%	100 150 200 250 167 INSUFFICIENT DATA	10 20 30 9.5 21.5	5 10 15 20 6.4 9.3	6 4 2 0 20 40 60
Euro 2 Petrol	753 18,450	19 16	1% 6%	149 189	10.8 21.3	5.2 13.4	6 4 2 0 20 40 60
Euro 3 Diesel	1,531 25,385	14 11	1% 4%	158 177	10.8 21.2	5.7 8.7	6 4 2 0 20 40 60
Euro 3 Petrol	6,370 34,545	15 12	1% 5%	175 176	10.8 20.4	5.2 11.1	6 4 2 0 20 40 60
Euro 4 Diesel	6,984 54,746	10 7	1% 5%	162 164	10.7 20.7	5.6 10	6 4 2 0 20 40 60
Euro 4 Petrol	11,833 83,338	10 8	1% 7%	161 169	10.8 21	5.3 13.8	6 4 2 0 20 40 60
Euro 5 Diesel	12,935 70,760	5 3	2% 5%	136 140	10.6 20.9	5.9 11.6	6 4 2 0 20 40 60
Euro 5 Petrol	11,131 65,230	5 4	1% 7%	129 139	10.7 20.9	5.6 14.2	6 4 2 0 20 40 60
Euro 6 Diesel	9,536 23,650	2 1	1% 5%	119 125	10.6 21.8	6.5 10.9	6 4 2 0 20 40 60
Euro 6 Petrol	8,671 19,347	2 2	2% 6%	119 126	10.6 21.9	6 13.2	6 4 2 0 20 40 60

EMISSIONS RESULTS: PASSENGER CARS AND LIGHT COMMERCIAL VEHICLES

This section presents emissions results for light-duty vehicles. The primary focus is on passenger cars, which are the most prevalent vehicle type in the London 2017–2018 dataset, as well as the CONOX remote sensing database. Passenger car NO_x, CO, and PM emissions are considered. Additional NO_x results for light commercial vehicles also are presented.

NITROGEN OXIDES

Figure 4 presents average fuel-specific NO_x emissions of light-duty vehicles in grams NO_x per kilogram fuel (g/kg) from the full CONOX dataset. NO_x emissions by fuel type and emission standard are similar for passenger cars and light commercial vehicles. NO_x emissions from petrol vehicles declined as emission limits tightened from Euro 2 to Euro 6. Diesel NO_x emissions, however, remained fairly stable from Euro 2 to Euro 5 and fell significantly only with the Euro 6 standard. This pattern is consistent with previous remote sensing measurements¹⁰ and measurements conducted using portable emissions measurement systems (PEMS).¹¹

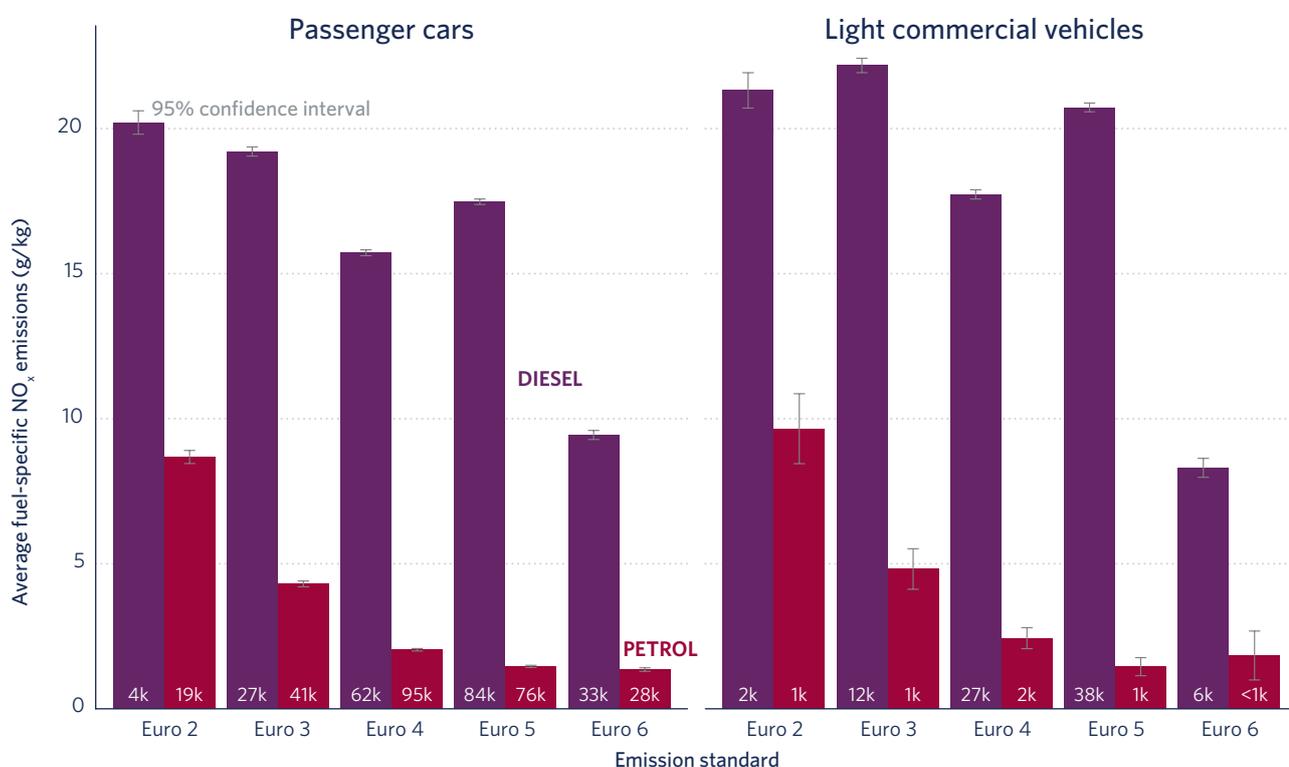


Figure 4. Average fuel-specific NO_x emissions by fuel type and Euro standard for passenger cars and light commercial vehicles. Notes: The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean.

10 Bernard et al., *Determination of Real-World Emissions*.
 11 Jens Borken-Kleefeld et al., *Comparing Emission Rates Derived from Remote Sensing with PEMS and Chassis Dynamometer Tests—CONOX Task 1 Report* (Federal Office for the Environment, Switzerland, May 2018), <https://www.ivl.se/download/18.2aa26978160972788071cd7b/1529408235244/comparing-emission-rates-derived-from-remote-sensing-with-pems-and-chassis-dynamometer-tests-conox-task1-report.pdf>

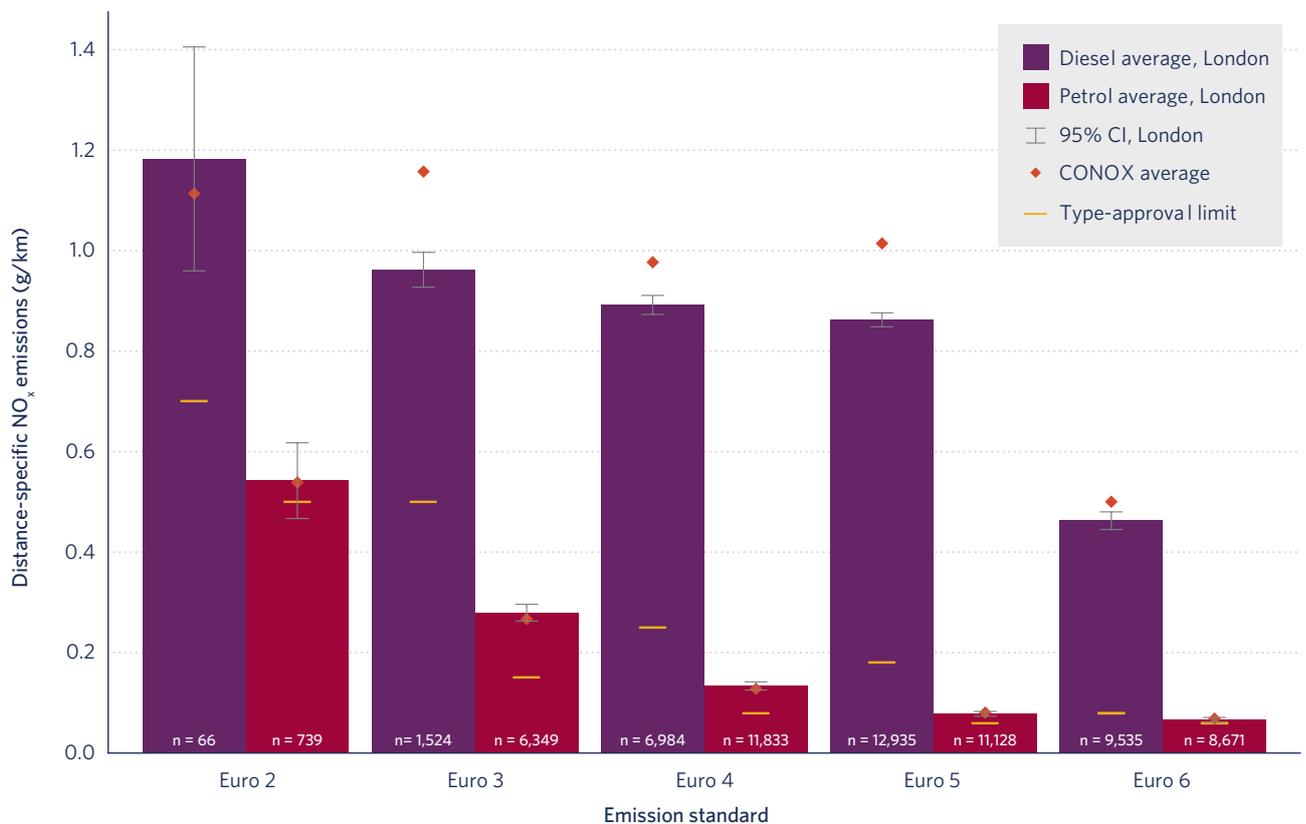


Figure 5. Average distance-specific NO_x emissions from Euro 2 to Euro 6 petrol and diesel passenger cars in the London 2017–2018 and CONOX remote sensing data

Notes: The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean.

Fuel-specific NO_x emissions can be converted to distance-specific emission values, in grams of NO_x per kilometer travelled (g/km), by estimating the amount of fuel burnt per kilometer driven (kg/km). Distance-specific fuel consumption is estimated by retrieving type-approval CO₂ values for each vehicle and correcting that value for real-world performance.¹² This methodology was detailed in a previous TRUE study.¹³ Figure 5 plots average distance-specific NO_x emissions of passenger cars in the London 2017–2018 data compared with the complete CONOX remote sensing dataset. As observed in Figure 4, NO_x emissions from petrol passenger cars declined with tightening emission standards, and Euro 5 and Euro 6 averages are within 1.35 times the petrol emission limits. Average NO_x emissions from Euro 5 and 6 diesel cars, however, are approximately 6 times higher than their respective laboratory emission limits.

Figure 5 shows that average NO_x emissions tended to be lower in the 2017–2018 London data than in the full CONOX database. Some of the differences can be explained by driving conditions. As shown in Table 2, power demand was considerably higher in the CONOX data—more specifically at Zurich measurement locations—than in London. Figure 6 uses generalized additive models to explore the relationship between VSP and NO_x emissions of Euro 3 to Euro 6 diesel passenger cars and shows that emissions tend to increase with VSP above 4 to 8 kW/t.¹⁴ This finding is in line with previous research.¹⁵ The models predict higher average NO_x emissions for CONOX data than for the London data, but some of the difference remains unexplained and may be linked to measurement artifacts.

12 Uwe Tietge et al., *From Laboratory to Road: A 2017 Update of Official and 'Real-World' Fuel Consumption and CO₂ Values for Passenger Cars in Europe* (ICCT: Washington, DC, November 5, 2017), <http://theicct.org/publications/laboratory-road-2017-update>

13 Bernard et al., *Determination of Real-World Emissions*.

14 Simon N. Wood, "Fast Stable Restricted Maximum Likelihood and Marginal Likelihood Estimation of Semiparametric Generalized Linear Models," *Journal of the Royal Statistical Society: Series B (Statistical Methodology)* 73, no. 1 (January 2011): 3–36, <https://doi.org/10.1111/j.1467-9868.2010.00749.x>

15 David C. Carslaw et al., "The Importance of High Vehicle Power for Passenger Car Emissions," *Atmospheric Environment* 68 (April 2013): 8–16, <https://doi.org/10.1016/j.atmosenv.2012.11.033>

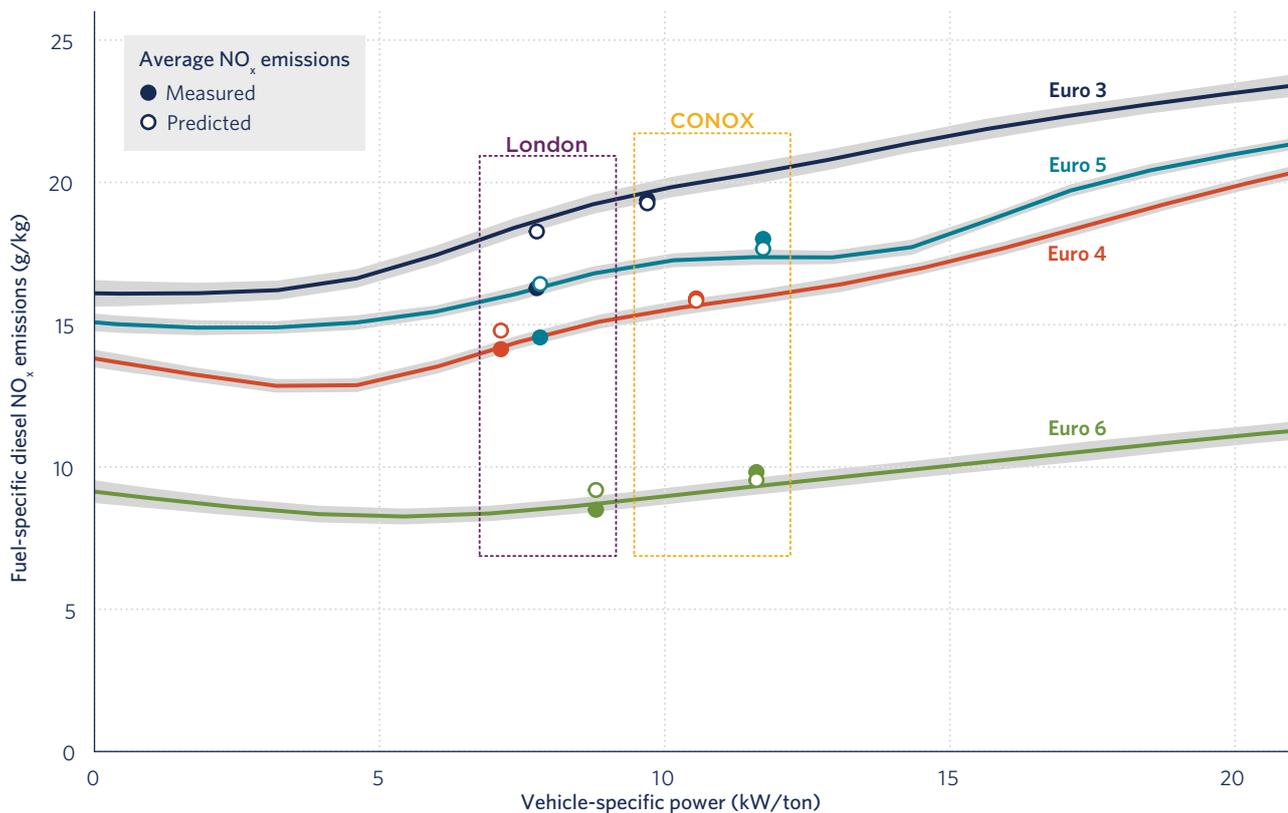


Figure 6. Fuel-specific NO_x emissions of diesel passenger cars as a function of VSP.
 Notes: Relationship represented using generalized additive models based on the full CONOX dataset. Markers denote average VSP as well as average measured NO_x emissions (filled markers) and average model predictions (unfilled markers) for London and CONOX data.

A new element of the Euro 6 regulation, known as Real Driving Emissions (RDE) introduces an on-road type-approval test that is predicted to lead to lower real-world emissions—specifically lower NO_x emissions from diesel vehicles. The RDE regulation began phase-in starting in September 2017 and will be fully implemented by January 2021 for passenger cars and by January 2022 for all light-duty vehicles. It is likely that a small fraction of Euro 6 vehicles measured during the London campaign were type approved under RDE because only a few models were available on the market. However, we were not able to differentiate RDE and non-RDE Euro 6 models as part of this study. Therefore, results are representative

of the average Euro 6 model measured during the testing campaigns.

Figure 7 plots distance-specific NO_x emissions from Euro 6 diesel and petrol cars by manufacturer group. London 2017–2018 data are plotted as bars to showcase the new measurements, which are compared to the full CONOX database (orange diamonds). Manufacturer groups were defined as clusters of car brands designed to reflect ownership structures. The Volkswagen Group, for instance, consists of the Audi, SEAT, Škoda, and VW brands, among others. (See Appendix for a full list of manufacturer groups and brands).

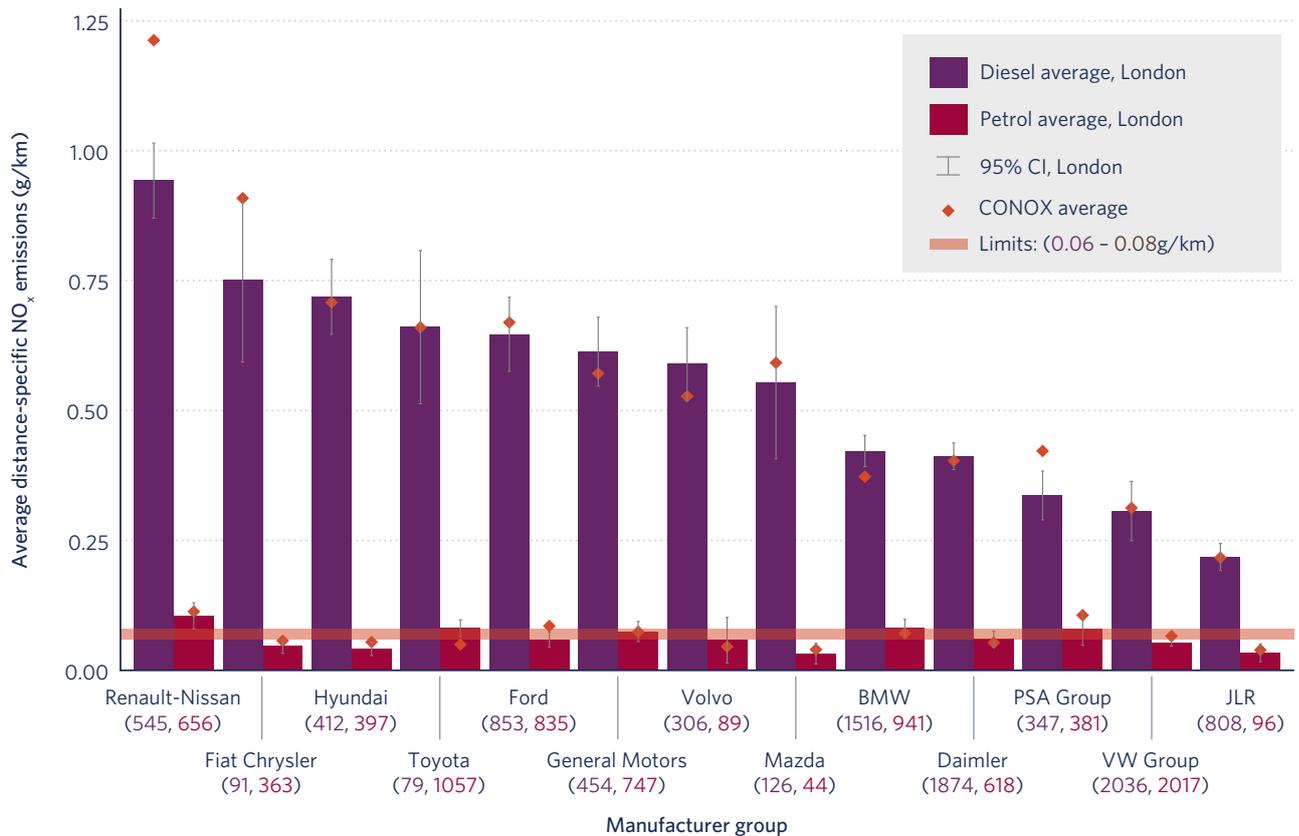


Figure 7. Average distance-specific NO_x emissions from Euro 6 diesel and petrol cars by manufacturer group.
 Notes: London 2017–2018 averages are presented as bars, CONOX averages as diamonds. The number of measurements per fuel type is presented in parentheses. Whiskers represent the 95% confidence interval of the mean.

Figure 7 again shows sizeable differences between diesel and petrol car NO_x emissions. While most manufacturer groups come close to meeting the petrol Euro 6 laboratory limit of 60 mg/km on the road, diesel vehicles consistently exceed their 80 mg/km laboratory limit. The on-road performance of diesel cars varies by manufacturer group, with the best-performing manufacturer, Jaguar Land Rover (JLR), exceeding the limit by 2 times and the worst-performing manufacturer, Renault-Nissan, on average exceeding the limit by 11 times according to London 2017–2018 data. Results from London measurements were congruent with CONOX results for the most part: Average diesel results

are within ±10% for eight out of 13 manufacturers, and within ±20% for 11 out of 13 manufacturers. Renault-Nissan and Fiat Chrysler saw the largest absolute difference between London and CONOX results, -0.27 and -0.16 g/km respectively. These differences may be explained by the higher VSP levels in the CONOX data (see Figure 6). Whether the relationship between NO_x emissions and VSP differs by manufacturer group will be explored in future research. The results presented in Figure 7 reiterate that diesel cars routinely exceed laboratory limits on NO_x emissions and indicate that NO_x emission levels vary significantly across manufacturer groups.

CARBON MONOXIDE

Remote sensing CO data presented here focus on emissions from petrol passenger cars, because diesel engines typically have low CO emissions due to lean fuel combustion conditions. Analysis of the CONOX database showed average distance-specific CO emissions for diesel cars across all Euro standards were below respective laboratory limits; CO limits for diesel cars are about half the limits for petrol cars.

Figure 8 plots mean and median distance-specific CO emissions for petrol passenger cars by Euro standard. Results from the 2017-2018 London remote sensing campaign (in blue) are consistently higher than CONOX results (in brown) across all Euro standards, and means are consistently higher than medians. Mean emissions calculated for petrol cars in the CONOX data are at or below respective laboratory limits for Euro 2 through 6 vehicles. In contrast, mean CO emissions measured in London in 2017-2018 exceed laboratory limits for Euro 2 through 5 vehicles.

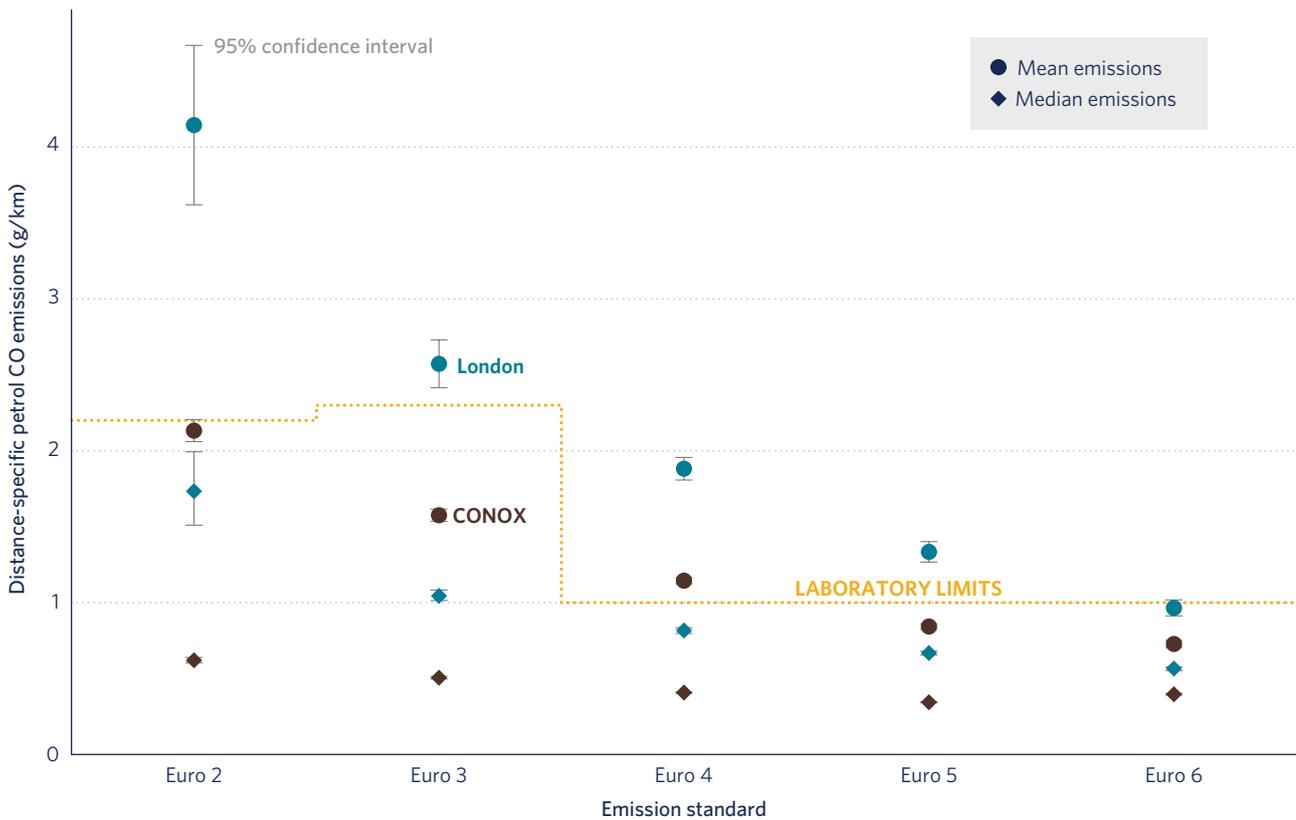


Figure 8. Average distance-specific CO emissions from petrol passenger cars by Euro standard.

Notes: Whiskers represent the 95% confidence interval of the mean.

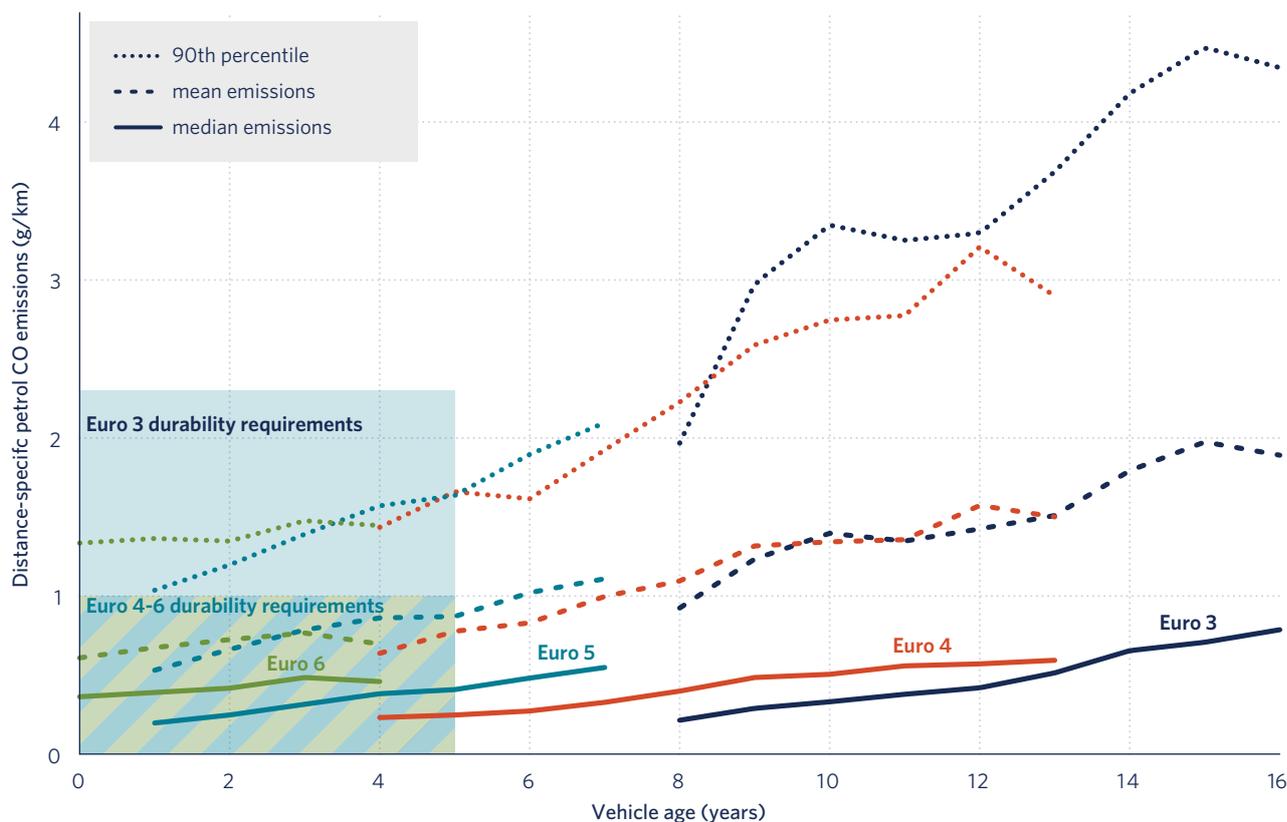


Figure 9. Median, mean, and 90th percentile CO emissions per Euro standard of petrol passenger cars over vehicle age. Notes: The rectangular grid represents durability requirements for Euro 3-6.

Figure 9 plots mean, median, and 90th percentile CO emissions of petrol passenger cars as a function of vehicle age. Median emissions were estimated using generalized additive models;¹⁶ median and 90th percentile emissions were estimated using quantile regression.¹⁷ The age ranges are truncated, from 5th to 95th percentile per Euro standard, to avoid plotting relationships for ranges with scarce data.¹⁸ The figure shows that CO emissions of petrol-fueled passenger cars increase with vehicle age, symptomatic of deterioration of the exhaust aftertreatment systems. This effect has been documented in previous studies.¹⁹ The increase in CO emissions over time explains why emissions measured in London in 2017-2018 were higher than other CONOX data: Because the London data are more recent than most of the other CONOX

data, vehicles measured in London have aged and deteriorated more than vehicles from the same Euro standard measured at other locations.

Figure 9 also illustrates why mean CO emissions significantly exceed median emissions in Figure 8. Although mean, median, and 90th percentile CO emissions increase with vehicle age, 90th percentile emissions increase at a considerably steeper rate than mean or median emissions, indicating that a subset of vehicles deteriorates much more than the bulk of vehicles. The vehicles with comparatively poor durability inflate the mean but have little effect on the median. Median CO emissions meet Euro 3-6 emission limits, even at ages up to 16 years. Although mean values still meet their respective Euro 3-6 emission limits within the Euro standards' durability requirements (up to 5 years), they exceed emission limits after 8 years in the case of Euro 4 passenger cars and after 6 years in case of Euro 5 passenger cars. Considering that 90th percentile emissions exceed emission limits within 0 to 3 years, some vehicles may not meet CO limits, or may only do so under certain driving conditions.

16 Wood, "Fast Stable Restricted Maximum Likelihood."

17 Roger Koenker, "Quantreg: Quantile Regression," 2018, <https://CRAN.R-project.org/package=quantreg>

18 Jens Borken-Kleefeld and Yuche Chen, "New Emission Deterioration Rates for Gasoline Cars - Results from Long-Term Measurements," *Atmospheric Environment* 101 (January 2015): 58-64, <https://doi.org/10.1016/j.atmosenv.2014.11.013>

19 Sjödin et al., "Real-Driving Emissions."

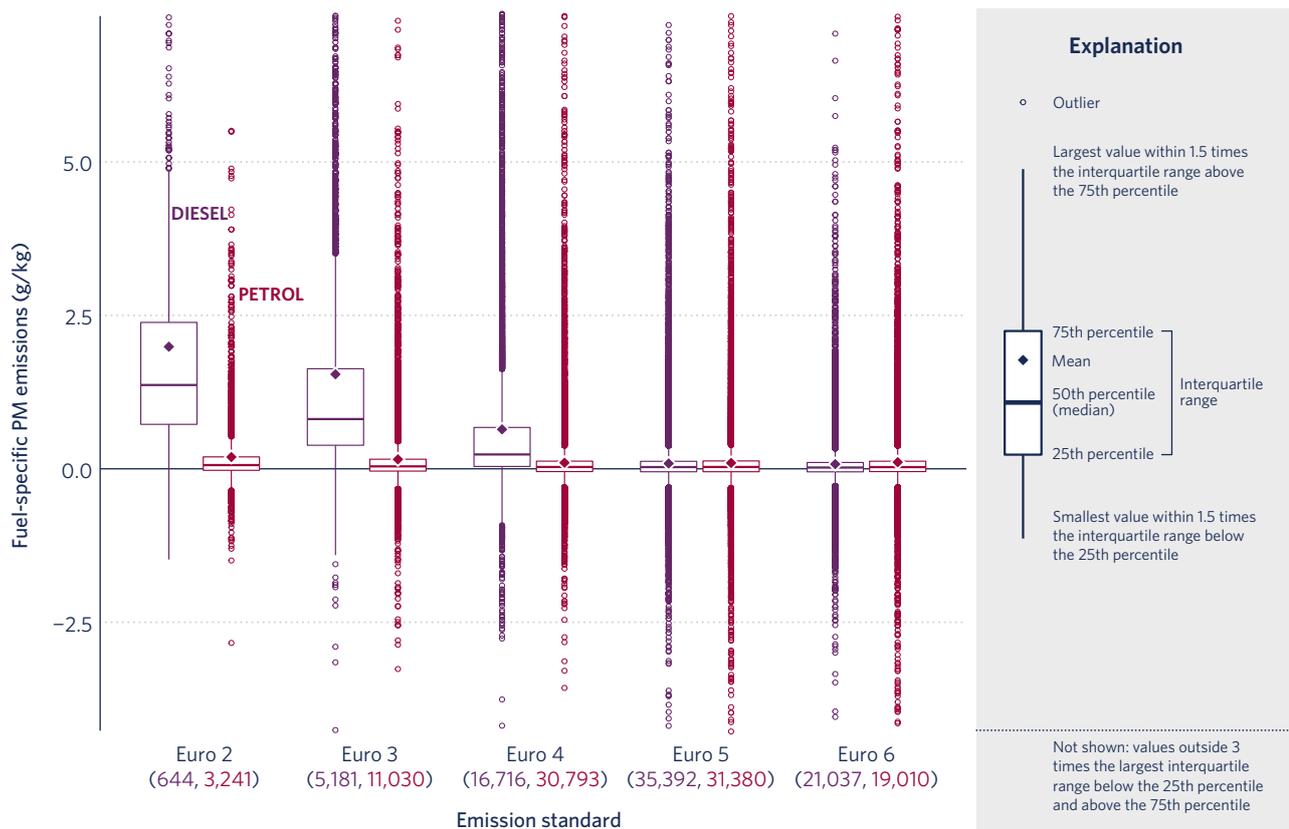


Figure 10. Boxplot of fuel-specific PM emissions of passenger cars by Euro standard and fuel type.
 Notes: The number of measurements is presented in parentheses. An explanation of boxplots is presented at the right.²¹

PARTICULATE MATTER

The RSD5000 remote sensing instrument used in this study measures exhaust plume opacity as a proxy for particulate matter emissions. Opacity is a measure of the amount of light of a given wavelength, in this case 230 nm, that is absorbed or scattered by particles in a test vehicle's exhaust plume. The interaction of the remote sensing light beam with exhaust particles is complex and dependent on a number of factors, including the physical and chemical characteristics of the exhaust particulate matter. These factors can vary considerably across vehicles in a fleet and even for individual vehicles across operating modes. While the opacity measurement gives some information about particulate matter emissions, it is fundamentally different than methods used to quantify particulate matter mass and particle number emissions in regulatory certification and compliance testing.

Remote sensing opacity measurements typically are normalized to vehicle fuel consumption and reported as PM emissions in units of g/kg fuel. In general, the remote sensing opacity measurement is useful for

evaluating PM emissions from older diesel and high-emitting vehicles. The approach is less useful for quantifying PM emissions from properly functioning petrol vehicles and modern diesel vehicles equipped with particulate filters, as exhaust opacity readings for these vehicles are expected to fall within the noise band of the instrument.²⁰ Furthermore, PM mass emissions are not necessarily correlated with particle number emissions. High particle number emissions with low PM mass emissions is a known concern for vehicles powered by gasoline direct injection engines.

Figure 10 plots fuel-specific PM emissions from diesel and petrol passenger cars by Euro standard in the full CONOX dataset. The figure indicates that petrol PM emissions historically have been low. In contrast, mean and median diesel PM emissions significantly declined

²⁰ Environmental Systems Products Holdings, *Smoke factor measurements with remote sensing device technology: Recommended practice*, (November 2010), http://opusinspection.com/wp-content/uploads/2016/02/20101110_ESP-RSD-Smoke-Factor-Final-Document.pdf

²¹ Laura DeCicco, "Exploring Ggplot2 Boxplots - Defining Limits and Adjusting Style," (U.S. Geological Survey, March 16, 2016), <https://owi.usgs.gov/blog/boxplots/>



from Euro 2 to 4 and leveled off at petrol-like levels—below the detection level of the RSD5000 instrument—with the widespread adoption of diesel particulate filters from Euro 5 onward.²²

The plot also indicates that there is a wide spread in PM measurements from remote sensing devices and that high outliers are more common than low outliers, which explains why mean emissions are consistently higher than median emissions. The extent to which outliers result from tampered or malfunctioning exhaust aftertreatment systems (e.g., removal of diesel

particulate filter) is impossible to determine without repeated measurements of individual vehicles. Robust methods also need to be developed to differentiate between high-emitting vehicles and occasional high emission events, for instance due to filter regeneration. Overall, all measures of PM emissions from petrol and diesel cars have declined to historical lows with the introduction of Euro 5. PM measurements from remote sensing may become a source of valuable information on vehicle tampering, but more data and robust methods are needed.

22 David Carslaw, “Remote Sensing: Demonstrating Diesel Particulate Filter Success,” *Ricardo*, August 17, 2017, <https://ee.ricardo.com/News/Remote-sensing-demonstrating-diesel-particulate-fi>

CASE STUDY: TAXIS

Black taxis are a well-known London-specific mode of transportation, with technical vehicle requirements set by the city. The majority of taxis were manufactured and sold by a single company, The London Taxi Company, and diesel engines used in Euro 4 to 6 black taxis were produced by the Italian diesel engine manufacturing company VM Motori, which is fully owned by Fiat Chrysler Automobiles. In general, the black taxis follow the same emissions standards as diesel passenger cars. However, for regulation prior to Euro 6, black taxis qualified for a special exemption that allowed for certain diesel vehicles to be classified as a commercial vehicle (category N1 Class 3). Therefore, Euro 5 black taxis are subject to a more lenient emissions limit of 280 mg/km, instead of the 180 mg/km required of Euro 5 diesel passenger cars (category M1). This exemption was eliminated under Euro 6.

London has implemented some measures to reduce emissions from black taxis. In 2017, subsidies were offered to taxi drivers who scrapped older taxis and additional grants were offered to subsidize the cost of purchasing a new Zero Emissions Capable (ZEC) taxi. In addition, as of January 1, 2018 no more new diesel

taxis will be licensed in London. The ZEC taxis will utilize mostly plug-in hybrid (with petrol engine) technology and vehicle charging locations have been installed across the city to support the use of these vehicles. London has established an Ultra Low Emission Zone (ULEZ) which will begin in April of 2019. Pre-Euro 6 diesel cars will not be permitted within the zone without paying an additional daily charge. Black taxis have received an exemption to this requirement, however taxis are currently subject to a 15-year age limit.

Figure 11 compares distance-specific NO_x emissions from London black taxis with diesel passenger cars measured in London in 2017–2018. Taxi measurements were compiled from several remote sensing campaigns. Euro 2–3 taxis were measured almost exclusively in earlier campaigns, in 2012–2015, and across different cities in the UK. Note that although the black taxi is a London icon, the same model is also sold and commonly utilized in a number of cities in the UK. In contrast, measurements in London in 2017–2018 were mostly Euro 4 and 5 taxis.²³ Fewer than 30 measurements were collected for Euro 6 taxis and thus are not presented in the figure.

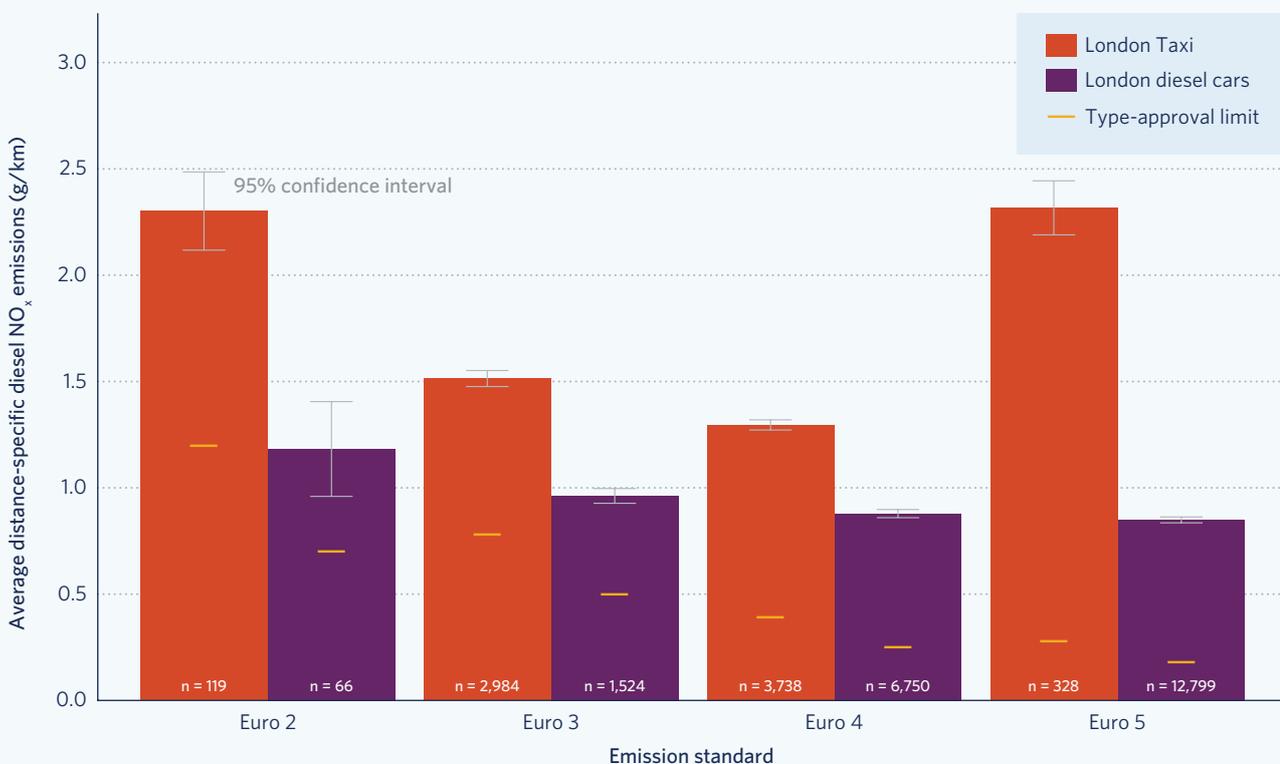


Figure 11. Distance-specific NO_x emissions from diesel-fueled London taxis compared with other London diesel passenger cars by Euro standard. Notes: The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean.

²³ For this case study, the core dataset collected using the RSD5000 instrument is supplemented with additional data collected with the FEAT RSD.



Figure 12. Distance-specific NO_x emissions from diesel-fueled London taxis by Euro standard measured in the laboratory and by remote sensing.

Results presented in Figure 11 indicate that NO_x emissions from London taxis consistently exceeded diesel passenger car emissions. This finding is consistent with previous research.²⁴ Even after accounting for the different emission limits, taxis emitted up to 7 times their laboratory limits, while regular diesel passenger cars emitted 4 times their limits. The Euro 5 taxis are the highest emitters, emitting, on average, at least 50% more NO_x per kilometer than Euro 3 and 4 taxis.

In contrast to NO_x emissions, PM emissions from London taxis were found to be similar to those from diesel passenger cars for vehicles certified to Euro 4 and 5 standards. The remote sensing data show the PM emissions performance of Euro 5 taxis to be improved relative to Euro 4 taxis, with a similar level of reduction in mean fuel-specific PM emissions to that observed for the aggregate diesel car sample shown in Figure 10.

The remote sensing results for London taxis are in line with laboratory testing results commissioned by Transport for London (TfL). As part of their ongoing emissions modeling work, TfL commissioned laboratory testing of Euro 4, 5, and 6 black taxis over a customized London cycle made of

three sections designed to represent driving conditions in inner, central, and outer London.²⁵ Figure 12 compares NO_x emissions of black taxi for Euro 2 through 6 taken by both remote sensing and laboratory measurements. Laboratory results are shown for the individual sections as well as the combined cycle that represents driving all across London. Remote sensing data are available for Euro standards 2 through 5, and laboratory data are available for Euro standards 4 through 6. For the two Euro standards (Euro 4 and 5) where both remote sensing and laboratory data are available, we find that the two data sources correlate reasonably well. For Euro 4, the average of the remote sensing results is 52% higher than the “combined” cycle result. For Euro 5, the remote sensing results are 7% lower than the “combined” cycle result.

There are two key findings from our analysis of the London remote sensing data:

- Black taxis have, on average, higher emissions than diesel cars covered by the same emissions standard. This is especially true for Euro 5 taxis, which emit close to 3 times the average emissions of a London diesel car.
- Remote sensing and laboratory testing are again shown to produce similar real-world emissions results.

24 David C. Carslaw and Glyn Rhys-Tyler, “New Insights from Comprehensive On-Road Measurements of NO_x, NO₂ and NH₃ from Vehicle Emission Remote Sensing in London, UK,” *Atmospheric Environment* 81 (December 2013): 339–347, <https://doi.org/10.1016/j.atmosenv.2013.09.026>

25 Personal communication, Transport for London, August 2018

CASE STUDY: TRANSIT BUSES

London has adopted a number of innovative programs and policies to reduce emissions from buses operating in the city:²⁶

- **Retrofit programs:** In 2013, TfL retrofitted more than 1,000 Euro III buses with selective catalytic reduction systems to achieve Euro IV emissions performance. Prior to this, retrofit efforts focused on installing particulate filters on TfL buses, such that all buses operated by TfL were equipped with this technology by 2006.²⁷ Another retrofit program was initiated in 2017 to retrofit around 5,000 Euro IV and V diesel buses with exhaust systems capable of achieving Euro VI emissions performance; around 2,000 have been done to date.
- **Euro VI procurement:** London began procuring buses meeting Euro VI emissions performance ahead of the full implementation of Euro VI emission standards. All new buses entering the fleet must be Euro VI or cleaner.
- **Low emission zones:** In 2017, the Mayor of London announced 12 Low Emission Bus Zones. Buses operating in these zones are required to meet Euro VI or better emissions performance. The first two zones were delivered in 2017, with a further five completed in 2018 and the remaining five to be delivered by 2019. Beginning April 2019, all buses and coaches operating in the London Ultra Low Emission Zone will need to meet Euro VI standards to avoid being subject to a daily charge. In October 2020 standards for buses and coaches operating in the Low Emission Zone (LEZ), which covers the whole of Greater London, will be strengthened to Euro VI.
- **Hybrid and zero emission buses:** London has prioritized the purchase of hybrid buses for the TfL fleet. As of November 2018, diesel-electric hybrid buses accounted for approximately 30% of the fleet, including 3,000 Euro VI hybrid buses. As of 2018, all new double-deck buses entering the fleet will be Euro VI hybrids, battery electric, or hydrogen fuel cell. TfL also operates one of the world's largest zero emission bus fleets outside of China, including

117 battery electric buses and 10 fuel cell buses. The city has committed to making all single-deck buses operating in central London zero emissions by 2020 and the entire TfL fleet zero emissions by 2037, at the latest.

Remote sensing data collected in 2017–2018 offer some insights into the effectiveness of these policies. While evaluations of any specific policy are beyond the scope of this report, the 2017–2018 remote sensing data, when compared to similar data from previous years and disaggregated by specific vehicle attributes, allow for some investigation of long-term changes in emissions from London buses and the real-world performance of the current TfL fleet.

In total, emissions from 3,305 buses were measured during the 2017–2018 London remote sensing campaign. This sample includes 2,332 measurements made using the RSD5000 instrument during the core data collection phase of the study, supplemented with 973 records from the University of Denver FEAT instrument. Buses operated by TfL accounted for 84% of this sample and all buses were diesels or diesel-electric hybrids.

The average fuel-specific NO_x emission rate for all buses measured in 2017–2018 was estimated to be 12 g/kg. The leftmost panel of Figure 13 compares this result to the average bus NO_x emission rate measured in previous remote sensing studies conducted in London in 2012²⁸ and 2013.²⁹ In the approximately five-year period between these studies, average NO_x emissions from buses decreased by about 65%. The measured improvement in fleet-average bus NO_x emissions greatly exceeds emissions changes observed for other diesel vehicle fleets during the same time period. A similar comparison of 2012–2013 and 2017–2018 London remote sensing data shows a decrease of 22% in the average NO_x emissions from diesel passenger cars, whereas emissions from black taxis were found to have actually increased in the period between the remote sensing studies. It should be noted that these relative changes may be influenced by factors related to differences in the 2012–2013 and 2017–2018 remote

26 "Improving buses," Transport for London, accessed October 23, 2018, <https://tfl.gov.uk/modes/buses/improving-buses>

27 David C. Carslaw, "Evidence of an increasing NO₂/NO_x emissions ratio from road traffic emissions," *Atmospheric Environment* 39 (June 2005): 4793–4802, <https://doi.org/10.1016/j.atmosenv.2005.06.023>

28 Carslaw and Rhys-Tyler, "New Insights from Comprehensive On-Road Measurements."

29 David C. Carslaw et al., "Performance of optimized SCR retrofit buses under urban driving and controlled conditions," *Atmospheric Environment* 105 (March 2015): 70–77, <https://doi.org/10.1016/j.atmosenv.2015.01.044>

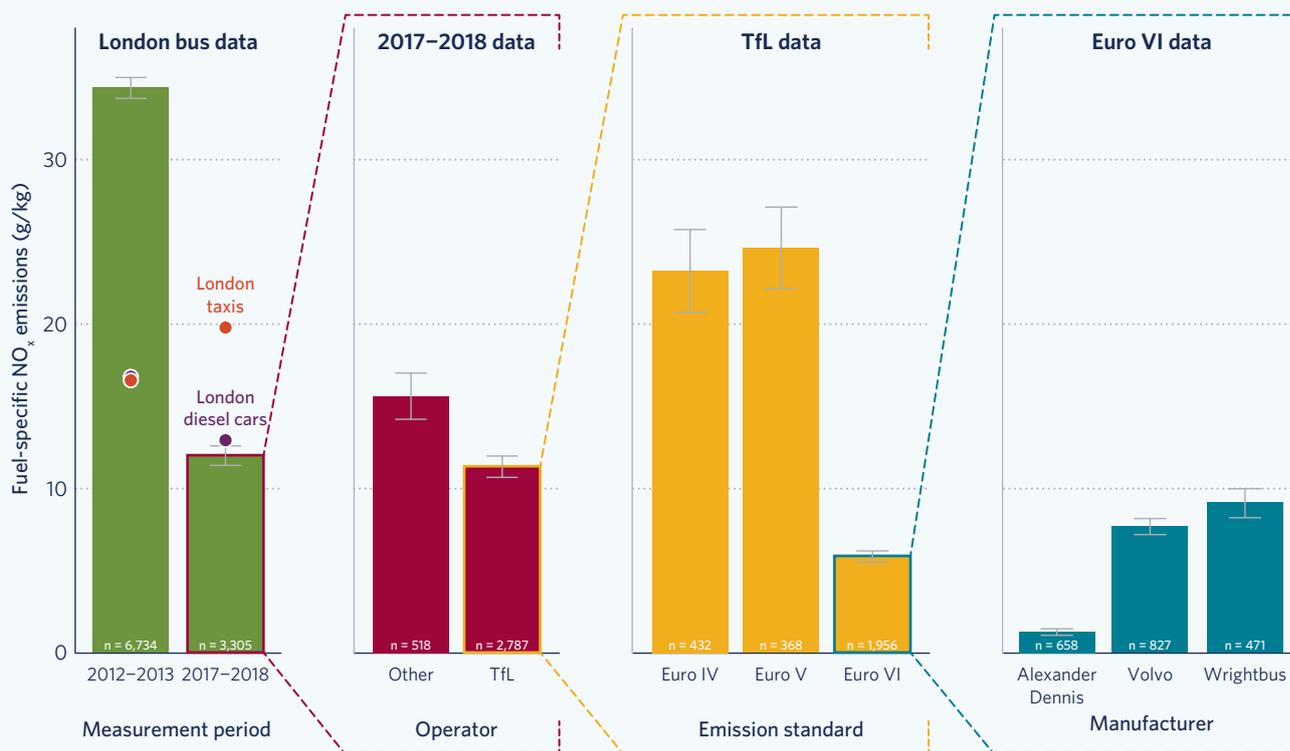


Figure 13. Average fuel-specific NO_x emissions from London buses.

sensing campaigns, such as sampling locations and ambient temperatures.

Average NO_x emissions from buses measured during the 2017-2018 campaign were found to be slightly lower than emissions from diesel passenger cars and 39% lower than emissions from black taxis on a fuel-specific basis. Conceptually, this means that, on average, the combustion of one liter of diesel fuel in a London bus will produce less NO_x emissions than if the same amount of fuel was used to power a diesel car or taxi.

The second panel of Figure 13 shows 2017-2018 London bus data by operator. TfL buses made up the majority of the sample and were found to have lower NO_x emissions on average than buses operated by other companies, 11.3 g/kg versus 15.6 g/kg. TfL buses in our sample tended to be newer than other buses—70% of sampled TfL buses were certified to Euro VI standards as compared with 36% of other buses—which could explain this result.

Further disaggregation of the 2017-2018 remote sensing data for TfL buses by emission standard is shown in the third panel of Figure 13. Euro VI was the most common standard for TfL buses observed during the study (70% of TfL buses), followed by Euro IV (16%) and Euro V (13%). No statistical difference was

observed in emissions from Euro IV and V buses, even though the Euro V type-approval NO_x limit is 40% lower than the Euro IV limit. These data support previous findings regarding the relatively poor performance of Euro V emission control systems in urban operating conditions.³⁰ In contrast, with respect to NO_x emissions, Euro VI buses appear to be performing well in real-world driving conditions. The average fuel-specific emission rate for these buses, 5.9 g/kg, is 74% lower than the Euro V emission rate. Notably, fuel-specific NO_x emissions from Euro VI buses also are 38% lower than the emissions from Euro 6 diesel passenger cars included in the CONOX database (see Figure 4). These findings support policies promoting increased uptake of buses meeting Euro VI emissions performance in the TfL fleet and the establishment of Euro VI standards for buses in the London ULEZ and LEZ.

Some variability in Euro VI emissions performance by bus manufacturer was observed. TfL buses are supplied primarily by three manufacturers—Alexander Dennis, Volvo, and Wrightbus. The Alexander Dennis and Wrightbus buses measured in this study were

³⁰ Sarah Chambliss and Anup Bandivadekar, *Accelerating progress from Euro 4/IV to Euro 6/VI vehicle emissions standards*, (ICCT: Washington, DC, March 2015), https://www.theicct.org/sites/default/files/publications/ICCT_EuroVI_briefing_20150304.pdf

equipped with engines manufactured by Cummins, whereas Volvo buses were powered by Volvo engines. Average NO_x emissions from Euro VI buses from each manufacturer were well below average emissions measured for Euro IV and Euro V buses. However, Alexander Dennis buses were found to have average NO_x emissions significantly lower than buses from other manufacturers. These findings are in line with recent PEMS measurements conducted by the UK Department for Transport, which found NO_x emissions for a Euro VI certified Wrightbus bus to be 3–4 times the emissions of Euro VI buses manufactured by Alexander Dennis.³¹ Further investigation of the characteristics of the best performing Euro VI buses in the TfL fleet (e.g., engine and aftertreatment calibrations, maintenance practices), while beyond the scope of this study, would be useful in identifying ways in which the emissions performance of the existing Euro VI fleet could be improved.

Average fuel-specific PM emissions for Euro IV through VI TfL buses were similar and at a level comparable to what was measured for Euro 5 and 6

diesel passenger cars. This indicates efforts to equip TfL buses with particulate filters have been effective in controlling PM emissions from the fleet, in particular for older diesel buses that may not have otherwise utilized this control technology.

In summary, 2017–2018 remote sensing data indicate clean bus policies and programs adopted by London have proven effective in reducing NO_x emissions from buses operating in the city. Fleet-average emissions have fallen by 65% over the past 5 years. For TfL buses, observed emissions decreases are likely attributable to transitions to Euro VI certified buses across the fleet. Our data show the real-world emissions performance of these buses to be significantly better than buses certified to Euro IV and V emission standards. Future real-world emissions testing of buses in London could be targeted at retrofit Euro IV and V buses to ensure that these vehicles are meeting Euro VI emissions performance, as is the stated goal of the retrofit program.

³¹ UK Department for Transport, *Vehicle market surveillance unit: Results of the 2017 programme*, (March 2018), https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/691601/vehicle-market-surveillance-unit-programme-results-2017.pdf

CASE STUDY: HIGH-EMITTING VEHICLE GROUPS

As we have shown earlier in this report, average real-world NO_x emissions can vary substantially among different vehicle groupings. These groupings range from broad categories, such as emissions standard and fuel type, to a more granular level, like vehicle families (all vehicles from a common manufacturer group and with the same engine displacement, fuel type, and emission standard). Coupled with information on vehicle fleet composition and vehicle-kilometers travelled, remote sensing data can be used to quantify the emissions footprint of a specific vehicle grouping. This information could be used for a number of purposes, including to inform measures that policymakers may take regarding specific types of vehicles.

Figure 14 shows an estimate of the total fraction of on-road passenger car NO_x emissions from each combination of emissions standard and fuel type in

London.³² Because we did not have the exact vehicle fleet composition for London, we instead used the remote sensing measurement share as a proxy for the share of each emissions standard/fuel type group. Vehicle-kilometers travelled were estimated based on national estimates of average annual mileage by fuel type and vehicle age.³³ Based on these assumptions, we estimate that although gasoline vehicles make up 55% of the passenger vehicles in London, they are responsible for only 11% of the NO_x emissions. In addition, we estimate that Euro 5 and older diesel cars are responsible for approximately 61% of the total passenger car NO_x emissions in London. Starting in April of 2019, when London's Ultra Low Emission Zone enters into effect, Euro 5 and older diesel vehicles operating in central London will be subject to a daily charge.



Figure 14. Estimated share of annual NO_x emissions and respective share of remote sensing measurements in Greater London differentiated by Euro standard and fuel type.

³² Note for this case study, the core dataset collected using the RSD5000 instrument is supplemented with data collected with the FEAT RSD.

³³ Craig Dun, Gareth Horton, and Sujith Kollamthodi, Improvements to the Definition of Lifetime Mileage of Light Duty Vehicles (Ricardo-AEA, March 3, 2015), https://ec.europa.eu/clima/sites/clima/files/transport/vehicles/docs/ldv_mileage_improvement_en.pdf



Figure 15. Average distance-specific NO_x emissions and share of remote sensing measurements for each vehicle family measured in London in 2017–2018.
 Notes: Marker size represent each vehicle family’s estimated share of NO_x emissions from passenger cars in Greater London. The top 10 vehicle families in terms of NO_x emissions share are labeled; more detailed information is provided in the Appendix. Laboratory limits for diesel cars are presented for context.

Figure 15 presents results similar to those in Figure 14, but the vehicles are grouped by family, as previously described. The results are plotted by distance-specific NO_x emissions versus share of remote sensing measurements during the London 2017–2018 testing campaigns. Each marker represents one vehicle family and the marker size represents the estimated share of NO_x emissions from passenger cars in Greater London. The results are differentiated by Euro standard and fuel type. Vehicle families with the highest average NO_x emissions are not necessarily those with the largest NO_x impact because there may be a smaller number

of those vehicles on the road or they might be driven less. For example, the Euro 5 family with the highest average NO_x emission is the 2.2 liter diesel engine from General Motors, but the family with the largest NO_x impact is the VW Group 2.0 liter diesel engine. The vehicle families with the 10 highest NO_x impacts are responsible for approximately 15% of the fleet and 32% of passenger car NO_x emissions in London. Data such as these could be utilized by policy makers to prioritize certain vehicle families for removal from the fleet, such as through scrappage or other incentive programs.

CONCLUSIONS

In the TRUE London remote sensing study, real-world vehicle emissions were measured at nine sites throughout Greater London in the winter of 2017–2018. Over the course of 41 days of sampling, emissions from more than 100,000 vehicles, mostly passenger cars and light commercial vehicles, were measured using remote sensing technologies. These data were collected over a range of ambient temperatures and driving conditions. The London data were added to a growing database of European remote sensing data, which now includes close to 1 million records.

Passenger cars and light commercial vehicles were the most common vehicle types in the London dataset, accounting for 71% and 21% of total remote sensing records, respectively. Analysis of data collected for these vehicle types shows that average NO_x emissions have fallen in recent years but there remains a large discrepancy between diesel and petrol vehicles, with NO_x from new diesel vehicles on average 7 times that of new petrol vehicles. Passenger car NO_x emissions results from the London sampling were coupled with information on vehicle fleet composition and vehicle-kilometers travelled to evaluate the emissions footprint of specific vehicle groups. Euro 5 and earlier diesel cars are estimated to be responsible for approximately 60% of the NO_x emissions from passenger cars in Greater London. This is the group of vehicles that will be excluded from central London as part of the upcoming Ultra Low Emission Zone.

Carbon monoxide emissions from passenger cars are significantly lower for newer vehicles and CO emissions for diesels are, on average, lower than those of petrol vehicles. For petrol cars, average CO emissions appear to increase as a vehicle ages and this increase is more pronounced for a small subsection of the fleet.

Particulate matter emissions from passenger cars are low for new diesel and gasoline cars. Diesel cars, Euro

5 and newer, equipped with diesel particulate filters demonstrate significantly lower PM emissions than those without this equipment.

Case studies were conducted to investigate emissions for diesel black taxis and transit buses operating in London. Results indicate diesel black taxis produce, on average, higher NO_x emissions than diesel passenger cars covered by the same emissions standard. The emissions performance of Euro 5 diesel taxis was especially poor, with NO_x emissions 3 times the emissions from Euro 5 diesel cars and up to 7 times the laboratory emission limit. The average NO_x emission rate for diesel black taxis was found to have increased by 18% when compared to results from remote sensing measurements made in London in 2012–2013. By contrast, emissions from transit buses in London have experienced a significant reduction in average NO_x emissions over the past 5 years. Average NO_x emissions from the transit bus fleet have decreased 65% between 2012–2013 and 2017–2018. Over the same period, average emissions from the diesel passenger car fleet decreased by 22%.

Remote sensing has been shown to be an effective tool to inform the public, researchers, and policymakers on real-world emissions characteristics of the vehicle fleet in a given city. The results presented here give some insights into the real-world emissions of London's current fleet. While average vehicle emissions have decreased in recent years, there are still a large proportion of high emitting vehicles on the road around the city. The results also help to evaluate the effectiveness of implemented policies. For example, it can be seen that policies put in place to reduce NO_x emissions from the bus fleet have been quite effective over the past 5 years. And finally, the results can be used to predict the impact of future policies. For example, the results of the analysis indicate that the upcoming Ultra Low Emission Zone will have a significant impact in reducing NO_x emissions in central London.

APPENDIX

Table A1. Vehicle brands by manufacturer group.

Manufacturer group	Vehicle brand
BMW	BMW
BMW	Mini
Daimler	Mercedes-Benz
Daimler	Smart
Fiat	Alfa Romeo
Fiat	Chrysler
Fiat	Fiat
Fiat	Iveco
Fiat	Jeep
Fiat	Lancia
Fiat	Maserati
Ford	Ford
General Motors	Chevrolet
General Motors	GMC
General Motors	Opel
General Motors	Vauxhall
Hyundai Motor Company	Hyundai
Hyundai Motor Company	KIA
Jaguar Land Rover	Jaguar
Jaguar Land Rover	Land Rover
Mazda	Mazda
PSA Group	Citroën
PSA Group	DS
PSA Group	Peugeot
Renault-Nissan	Dacia
Renault-Nissan	Infiniti
Renault-Nissan	Nissan
Renault-Nissan	Renault
Volkswagen Group	Audi
Volkswagen Group	Bentley
Volkswagen Group	Lamborghini
Volkswagen Group	Porsche
Volkswagen Group	SEAT
Volkswagen Group	Škoda
Volkswagen Group	Volkswagen
Volvo	Volvo

Table A2. Estimated share of passenger car NO_x emissions in London by vehicle family.

Emission standard	Rank	Fuel type	Manufacturer group	Engine displacement (l)	n	Avg. NO _x (g/km)	Estimated share of passenger car NO _x emissions
Euro 3	1	Diesel	BMW	2	48	0.9	0.1%
Euro 3	2	Diesel	BMW	2.9	33	1.2	0.1%
Euro 3	3	Diesel	BMW	3	62	1.2	0.2%
Euro 3	4	Diesel	Daimler	2.7	81	0.9	0.2%
Euro 3	5	Diesel	Daimler	3.2	36	1.1	0.1%
Euro 3	6	Diesel	General Motors	1.7	37	1	0.1%
Euro 3	7	Diesel	PSA Group	2	123	1.3	0.3%
Euro 3	8	Diesel	Volvo	2.4	36	1.1	0.1%
Euro 3	9	Diesel	VW Group	1.9	378	0.9	0.7%
Euro 3	10	Diesel	VW Group	2.5	36	1.4	0.1%
Euro 4	1	Diesel	Fiat Chrysler	2.8	79	1.3	0.3%
Euro 4	2	Diesel	General Motors	1.9	281	1.5	1.1%
Euro 4	3	Diesel	Hyundai	2	50	1.4	0.2%
Euro 4	4	Diesel	Renault-Nissan	2	80	1.7	0.3%
Euro 4	5	Diesel	Saab	1.9	90	1.3	0.3%
Euro 4	6	Diesel	JLR	2.7	201	1.2	0.6%
Euro 4	7	Diesel	JLR	3.6	67	1.7	0.3%
Euro 4	8	Diesel	VW Group	2.5	58	1.2	0.2%
Euro 4	9	Diesel	VW Group	2.7	72	1.6	0.3%
Euro 4	10	Diesel	VW Group	3	146	1.7	0.6%
Euro 5	1	Diesel	Ford	2.2	40	1.2	0.2%
Euro 5	2	Diesel	General Motors	2	640	1.7	3.7%
Euro 5	3	Diesel	General Motors	2	34	2	0.2%
Euro 5	4	Diesel	General Motors	2.2	41	2	0.3%
Euro 5	5	Diesel	Hyundai	2	98	1.6	0.5%
Euro 5	6	Diesel	Hyundai	2.2	53	1.5	0.3%
Euro 5	7	Diesel	Renault-Nissan	1.6	134	1.2	0.5%
Euro 5	8	Diesel	Renault-Nissan	2	55	1.7	0.3%
Euro 5	9	Diesel	JLR	3	638	1.2	2.6%
Euro 5	10	Diesel	VW Group	3	338	1.6	1.8%
Euro 6	1	Diesel	Daimler	1.5	196	0.9	1.0%
Euro 6	2	Diesel	Fiat Chrysler	1.6	30	0.8	0.1%
Euro 6	3	Diesel	Ford	2	557	0.8	2.5%
Euro 6	4	Diesel	Hyundai	2	56	1.1	0.4%
Euro 6	5	Diesel	Hyundai	2.2	50	1	0.3%
Euro 6	6	Diesel	Honda	1.6	57	0.9	0.3%
Euro 6	7	Diesel	Renault-Nissan	1.5	428	0.9	2.3%
Euro 6	8	Diesel	Renault-Nissan	1.6	158	1.1	1.0%
Euro 6	9	Diesel	Toyota	1.6	31	0.8	0.1%
Euro 6	10	Diesel	Volvo	2.4	47	0.9	0.2%

Note: Results are shown for the 10 vehicle families of each Euro standard with the highest measured g/km NO_x emission rates.



TO FIND OUT MORE

For details on the TRUE rating and related questions, contact Rachel Muncrief, rachel@theicct.org. For more information on the TRUE project, visit www.trueinitiative.org.

The Real Urban Emissions Initiative (TRUE) is a partnership of the FIA Foundation, the International Council on Clean Transportation, Global NCAP, Transport and Environment, and C40 Cities.

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