Remote sensing of motor vehicle emissions in Paris

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THE TRUE INITIATIVE

Studies have documented significant and growing discrepancies between the amount of 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 diesel vehicles make up a higher proportion of the light-duty vehicle fleet than in other regions. Poor real-world diesel NO_x emission control has contributed to persistent air-quality problems in many European cities and has adversely impacted public health.

The FIA Foundation and the International Council on Clean Transportation (ICCT), working with C40 Cities, the Global New Car Assessment Programme (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 to support 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. The first was conducted in London in winter 2017–2018. This paper presents results from the second pilot study, which was carried out in Paris in the summer of 2018.

EXECUTIVE SUMMARY

In March 2017, Paris Mayor Anne Hidalgo announced a commitment to make real-world vehicle emissions data available to the public. These data can support evaluations of policies aimed at reducing the negative impacts of vehicle pollution on air quality and human health, help in the development of evidence-based improvement initiatives, and provide consumers with information on the actual emissions of vehicles they own or are considering for purchase.

To support this commitment, The Real Urban Emissions initiative (TRUE) undertook a real-world emissions measurement study in Paris in summer 2018. The study used remote-sensing technology to measure emissions from more than 180,000 in-use vehicles at three locations in the city. Most of these vehicles were passenger cars and light commercial vehicles, though the sample also included significant numbers of buses, motorcycles, mopeds, and heavy-duty vehicles. The data were collected over a range of ambient temperatures and vehicle operating conditions. Notably, a significant number of measurements were made when ambient temperatures exceeded 30 °C, a range underrepresented in existing European remote-sensing data, and at an average vehicle power demand that tended to be lower than the average of existing European remote sensing data.

KEY FINDINGS

- Nitrogen oxide (NO_x) emissions from petrol passenger cars in Paris decline in step with the emissions standard the cars are certified to; i.e., a Euro 5 petrol car has significantly lower NO_x emissions than a Euro 2 petrol car. Diesel cars, in contrast, show little improvement from Euro 2 through Euro 5 emission standards, and Euro 6 diesel cars show only modest improvement.
- NO_x emissions from Euro 6 diesel cars in Paris are 4.8 times those of Euro 6 petrol cars on a distance-specific basis and 6 times laboratory limits. On average, NO_x emissions of Euro 6 diesel cars are only 18% lower than those of the oldest (Euro 2) petrol cars observed in the study, and are many times higher than the NO_x emissions of petrol cars certified to Euro 3–Euro 6 standards.
- NO_x emissions of diesel cars in Paris are sensitive to driving conditions and ambient temperature. Fuel-specific NO_x emissions tended to increase with increasing vehicle specific power, a surrogate for engine load, and at temperatures above 30 °C. In this study, NO_x emissions of Euro 5 and Euro 6 diesel cars measured at ambient temperatures above 30 °C were 20% to 30% greater than emissions when temperatures were between 20 and 30 °C. The NO_x emissions of diesel cars in Paris and other European cities where remote sensing measurements have been made are comparable for similar testing conditions.
- Using the share of remote sensing measurements as a proxy for the in-use fleet composition, we estimate that Euro 5 and Euro 6 diesel cars were responsible for 63% of total passenger vehicle NO_x emissions in Paris at the time of the field study. These vehicles qualify for Crit'Air 2 classification and so will be allowed to operate without restriction in the Paris low-emission zone (LEZ) until 2024.
- Emissions of carbon monoxide (CO) from the newest petrol passenger cars and light commercial vehicles in Paris are significantly lower than the emissions of older petrol light-duty vehicles in the city's fleet. Emissions of CO from diesel cars are low relative to petrol cars across all Euro standards.
- Trends in particulate matter (PM) emissions for passenger cars in Paris are consistent with those observed in other European remote sensing studies. While PM emissions from petrol cars have historically been low and have shown little change over time, diesel car PM emissions improved significantly with the use of diesel particulate filters for Euro 5 and Euro 6 cars and are now comparable to petrol car PM emissions.
- For most L-category vehicles, which include mopeds, motorcycles, and tricycles, CO and NO_x emissions have improved with the implementation of more stringent Euro standards. However, fuel-specific emissions from these vehicles are, on average, considerably higher than for petrol cars. When expressed on a fuel-specific basis, the CO, NO_x and PM emissions from these vehicles are high relative to other vehicle types that qualify for the Crit'Air 1 emissions classification, considered the cleanest classification for vehicles using internal combustion engines, like Euro 5 and Euro 6 petrol cars.

- The real-world NO_x emissions performance of Euro VI city transit and coach buses in Paris is considerably improved relative to Euro V buses. On average, NO_x emissions for Euro VI city transit and coach buses were 59% and 84% lower, respectively, than for Euro V buses. When expressed on a fuel-specific basis, NO_x emissions of Euro VI city transit buses operating in Paris were, on average, lower than the emissions of Euro 6 diesel cars.
- Under the range of test conditions observed in the study, average fuel-specific NO_x emissions of Euro 6d-TEMP diesel cars were around 70% lower than those of diesel vehicles certified to earlier stages of the Euro 6 regulation. For three of the four Euro 6d-TEMP diesel vehicle families for which we obtained more than 30 measurements, there was no clear dependence of NO_x emissions on VSP. Nevertheless, average fuel-specific NO_x emissions remain higher than for Euro 6 petrol cars, and early evidence suggests NO_x emissions at higher engine loads may be of concern for at least one of the Euro 6d-TEMP diesel vehicle families observed in the study.

KEY RECOMMENDATIONS

- Under current policies, all diesel cars, with the exception of plug-in hybrids, will be banned from the Paris LEZ beginning in 2024, when access restrictions will be tightened to allow only zero-emissions vehicles or vehicles with Crit'Air 1 classification within the zone. Pressure is mounting to relax these restrictions by allowing Euro 6d-TEMP and newer diesel cars to qualify for the Crit'Air 1 classification. But the data from this study indicate that diesel NO_x emissions remain much higher than petrol emissions. The evidence is insufficient to support firm conclusions about NO_x emissions from Euro 6d-TEMP diesels specifically at present. Furthermore, the long-term performance of Euro 6d-TEMP diesel cars, and their emissions under conditions outside the boundaries of the Real Driving Emissions (RDE) test specifications, have yet to be evaluated.
- Euro 4 L-category vehicles qualify for the Crit'Air 1 emissions class and will be allowed to operate without restriction within Paris until 2030, even though their fuel-specific emissions are generally many times higher than petrol cars. The City of Paris should take steps to prevent growth in on-road emissions from L-category vehicles within the Paris LEZ.
- Further research and testing is needed to obtain a clearer picture of emissions performance under a wider range of testing conditions, in particular very high ambient temperatures, and to ensure that only vehicles with low real-world emissions qualify for Crit'Air 1 classification.

ABBREVIATIONS

CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
EDAR	Emissions Detection and Reporting
g/kg	grams per kilogram fuel consumed
g/km	grams per kilometer travelled
HEAT	Hager Environmental & Atmospheric Technologies
HC	hydrocarbons
ICCT	International Council on Clean Transportation
LEZ	Low-Emission Zone
NEDC	New European Driving Cycle
nmol/mol	nanomoles per mole
NO	nitric oxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
PEMS	portable emissions measurement system
PM	particulate matter
$PM_{2.5}$	fine particulate matter, of diameter < 2.5 micrometers
RATP	Régie Autonome des Transports Parisiens (Autonomous Operator of Parisian Transport)
RDE	Real Driving Emissions
RSD	remote sensing device
SIV	Système d'Immatriculation des Véhicules (Vehicle Registration System)
TRUE	The Real Urban Emissions Initiative
VSP	vehicle specific power

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THE REAL URBAN EMISSIONS INITIATIVE

INTRODUCTION

In 2017, 1.3 million Parisians were potentially exposed to levels of air pollution that exceeded European Union ambient air quality standards. Roadside concentrations of fine particulate matter ($PM_{2.5}$) were up to 1.6 times air quality objectives, and nitrogen dioxide (NO_2) concentrations along main roads were, on average, twice the annual limit value.[1]

Motor vehicles are a major source of pollutant emissions in the city, and these emissions contribute significantly to the observed exceedances of air quality standards. The most recent air pollutant emission inventory compiled by Airparif estimates that road transport is responsible for 56% of nitrogen oxide (NO_x) emissions and 27% of $PM_{2.5}$ emissions in the Paris region.[2] These pollutants have harmful impacts on public health. ICCT research estimates that 1,100 premature deaths in Metropolitan Paris in 2015 were attributable to ambient $PM_{2.5}$ and ozone from transportation tailpipe emissions (nitrogen oxides are one of the main precursors to ozone formation). Transportation accounted for approximately one-third of all deaths from air pollution in Paris in that year.[3]

In response to the air quality problem faced by the city, and recognizing the important role motor vehicles play in creating it, Mayor Anne Hildago announced a commitment to make real-world vehicle emissions data available to the public at a March 2017 Air'volution event organized by C40 Cities.[4] The announcement was made jointly with the Mayor of London, Saddiq Khan. In each city, real-world emissions data will allow for the evaluation of existing policies, support new, evidence-based air quality improvement initiatives, and increase consumer awareness regarding the actual emissions from the vehicles they own or are considering for purchase. The TRUE initiative has commissioned vehicle emissions testing in each city to support these efforts.

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 that forms the basis of the TRUE real-world passenger vehicle emissions rating scheme.[5]

The first TRUE study was carried out in London in winter 2017–2018. Over the course of 41 days of sampling, the emissions from more than 100,000 in-use vehicles were measured. Findings from the study, published in December 2018, highlight the high real-world NO_x emissions from diesel passenger cars and light commercial vehicles operating in London compared to similar petrol vehicles. Investigation of specific fleets provided evidence of elevated NO_x emissions from diesel black taxis and demonstrated the effectiveness of policies put in place to reduce emissions from the London transit bus fleet.[6] The London data were also combined with similar data collected in other European cities and compiled in the CONOX remote sensing database. The addition of the London data expanded the database to close to 1 million records.[7]

This paper details the results from the second TRUE real-world emissions measurement study, which was carried out in Paris during summer 2018. Remote sensing technology was used to measure the emissions of more than 180,000 vehicles operating on the streets of Paris. Here we provide an overview of the field study, along with results of the analysis of the collected data. Findings from the Paris study are presented and compared against similar measurements made in other European cities. Additional analyses in this report investigate emissions from L-category vehicles (mainly two- and three-wheelers), buses, and the newest

1 Airparif, *Air Quality in the Paris Region: Summary 2017*, March 2018, https://www.airparif.asso.fr/_pdf/publications/bilan-2017-anglais20180829.pdf

2 Airparif, *Bilan des émissions atmosphériques en Île-de-France, Année 2015 - version décembre 2018*, April 2019, https://www.airparif.asso.fr/_pdf/publications/inventaire_emissions_idf_2015_20190329.pdf

3 Joshua Miller, *Health impacts of air pollution from transportation sources in Paris*, (ICCT: Washington, DC, February 2019), http://theicct.org/publications/fact-sheet-health-impacts-air-pollution-transportation-sources-paris

4 "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-toslash-air-pollution-on-city-streets

5 "TRUE rating," https://www.trueinitiative.org/true-rating

6 Tim Dallmann, Yoann Bernard, Uwe Tietge, Rachel Muncrief, *Remote sensing of motor vehicle emissions in London,* (ICCT: Washington, DC, December 2018), http://theicct.org/publications/true-london-dec2018

7 Yoann Bernard, "Real-world NOx emissions from remote sensing: An update of the TRUE rating," 17 December 2018, https://www.theicct.org/blog/staff/true-rating-update-dec2018

passenger cars in the fleet subject to Real Driving Emissions (RDE) regulatory testing requirements.

TRUE PARIS REMOTE SENSING STUDY OVERVIEW

The Paris vehicle remote sensing field study was carried out over a three-week period in the summer of 2018. Emissions measurements were made at three locations in the 12th and 13th *arrondissements*. The field study was led by Hager Environmental & Atmospheric Technologies (HEAT), with additional support and assistance provided by project partners, including the City of Paris. This section provides an overview of the data-collection phase of the study, including project objectives, a description of the remote sensing instrumentation, details of sampling locations, and an overview of the collected data. A more detailed treatment of the data-collection phase of the project can be found in a consultant report prepared by HEAT.[8]

OBJECTIVES

The overall objective of the Paris remote sensing study was similar to that of the first TRUE study carried out in London: measure the real-world emissions of at least 100,000 in-use vehicles under a range of operating conditions and traffic characteristics. The remote sensing method was selected in both cases because it allows for non-intrusive measurement of real-world emissions from large numbers of vehicles in a short period of time and a cost-effective manner.[9] The focus of this study was on light-duty vehicles—passenger cars and light commercial vehicles—which make up the majority of vehicles operating on the streets of Paris. However, the emissions from other vehicle types driving on the roads where remote sensing equipment was deployed were also measured. These vehicles include transit and coach buses, L-category vehicles (e.g. motorcycles, mopeds, tricycles), and heavy goods vehicles.

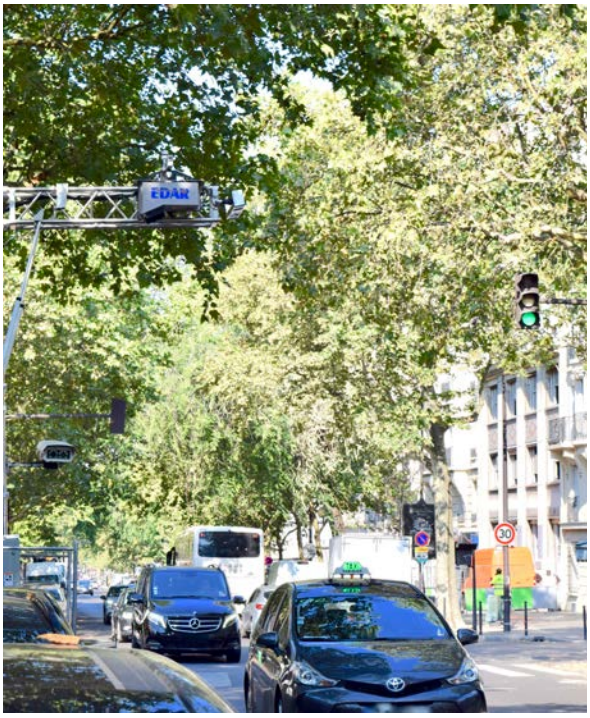
REMOTE SENSING INSTRUMENTATION

In this study, vehicle emissions were measured using the HEAT Emissions Detection and Reporting (EDAR) remote sensing instrument. Figure 1 shows one of the two EDAR units used in the field study deployed at the Boulevard Diderot sampling site. The EDAR system consists of a collection of components that collectively measure the emissions of the target vehicle and provide additional information about the vehicle operating and ambient weather conditions at the time of measurement. The components include:

- An emissions detection unit positioned above the target traffic lane. The EDAR instrument uses a laser light source which is swept across the width of the roadway and through the exhaust plume of the vehicle being measured. A reflective strip installed on the roadway reflects this light back to the detector. The light attenuation measured by the detection unit is proportional to the amount of specific pollutants in the vehicle's exhaust plume. The EDAR instruments used in this study measured carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxide (NO), nitrogen dioxide (NO_2), hydrocarbons (HC), and particulate matter (PM, via light extinction proxy).
- A laser-based rangefinder system to measure the vehicle's speed and acceleration. Speed and acceleration, along with road grade, are used to calculate vehicle specific power (VSP), a measure of the vehicle's instantaneous engine load during the measurement. This load is associated with the instantaneous emission rate measured by the emissions detection unit.
- An automatic license plate recognition camera to identify and transcribe the vehicle's license plate automatically when the vehicle's emissions are measured. The license plate number is used to retrieve the vehicle's technical information from registration databases without revealing vehicle owner information.
- Sensors to measure ambient conditions, including temperature, relative humidity, pressure, and wind speed and direction.

8 Hager Environmental & Atmospheric Technologies, "Paris Project with ICCT," 7 December, 2018. https://theicct.org/sites/default/files/HEAT_Paris_remote-sensing_2018.pdf

9 Tim Dallmann, *Use of remote-sensing technology for vehicle emissions monitoring and control,* (ICCT: Washington, DC, December 2018), http://theicct.org/publications/remote-sensing-briefing-dec2018



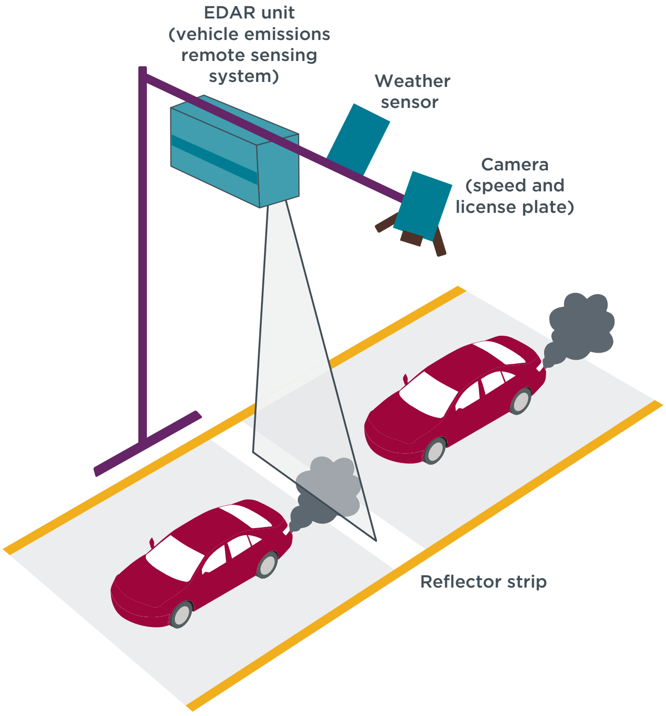


Figure 1. EDAR remote sensing instrument deployed at the Boulevard Diderot sampling site in the 12th arrondissement (left) and schematic of the main components of the EDAR system (right). (Photo courtesy of Hager Environmental & Atmospheric Technologies.)

A portable truss system was used to position the instrument package above the target traffic lane at each sampling location.[10]

In coordination with the City of Paris, vehicle technical information was retrieved from the Vehicle Registration System (SIV) at the Ministry of the Interior. A full listing of the technical information available from this database is available in the HEAT consultant report. A detailed data management plan was developed at the outset of the project to ensure the confidentiality of personally identifiable data, such as license plate number. This plan was approved by the Commission nationale de l'informatique et des libertés.

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

- The ambient background corrected concentration measurement of each emission species (CO, NO, NO_2, HC, PM) relative to CO_2
- 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, type-approval CO_2 value, and empty vehicle mass

SAMPLING SITES AND SCHEDULE

Vehicle emission measurements were made at three locations in the 12th and 13th *arrondissements* of Paris. Representatives from HEAT and the City of Paris conducted a preliminary site survey to identify suitable sampling locations for the project. Key evaluation criteria for site selection included high traffic counts, roadways with slight uphill grade to increase the likelihood of measuring vehicles under load, and continuous traffic flow.

The survey identified a number of sites meeting these criteria and suitable for the sampling campaign. Of these potential locations, four were targeted for the field study. Permit applications were submitted for each of these sites. Permission to deploy equipment was granted for three of the four locations, with construction and lane closures during the study period preventing sampling at the fourth location. The three sites, shown in Figure 2, were the Rue de Tolbiac at Rue Charles Fourier, Boulevard Diderot at Rue de Picpus, and the

10 A short video showing the deployment of the truss system in Paris can be found on the HEAT website, https://www.heatremotesensing.com/single-post/Truss-Deployment-Video

Paris sampling sites

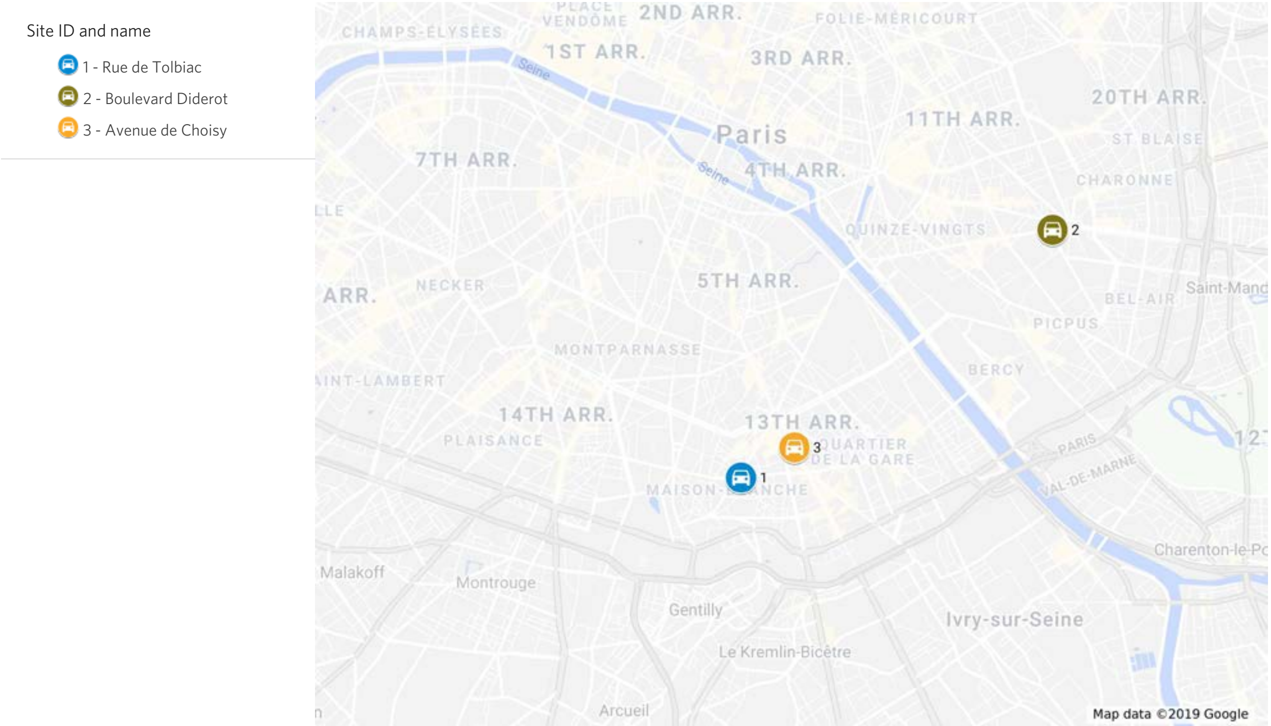


Figure 2. Measurement locations for the TRUE Paris 2018 remote sensing study.

Avenue de Choisy at Rue Georges Eastman. Each site is a two- or three-lane urban roadway with a posted speed limit of 50 km/h.

The field study was carried out from 20 June to 12 July 2018, with sampling conducted on a total of 22 days. During the study period, two EDAR instruments were deployed simultaneously at separate sites. One unit remained at the Boulevard Diderot site for the entire duration of the study. The other unit was deployed for 11 days at the Rue de Tolbiac site, followed by 11 days at the Avenue de Choisy site. Once the EDAR instrument was set up at a site and the reflective strip was installed on the roadway, sampling was conducted continuously, 24 hours a day for the duration of the deployment. HEAT engineers manually downloaded data from each instrument once per day.

Following the data-collection campaign, HEAT provided the City of Paris with a full list of the license plate numbers for the vehicles measured during the study. The City of Paris submitted the plate numbers to the Ministry of the Interior and vehicle technical information was returned in four months. The final dataset was pseudonymized by the City of Paris to remove any personally identifiable information, following the procedures established in the data management plan.

DATA COLLECTION SUMMARY

Table 1 presents an overview of the data-collection phase of the study, including the total sampling time and number of remote sensing records, or measurements of individual vehicles, for each site. The total records column shows the number of attempted individual vehicle remote sensing emission tests. In total, over 218,000 measurements were attempted during the three-week field study. Not all of these emission tests were successful; failures could be caused by factors such as a weak exhaust CO_2 signal or interference from other vehicles on the roadway. The valid emission record column of Table 1 shows the number of tests which were successful and yielded emissions data for the target vehicle. The study average valid measurement rate was 84%, ranging from 82% at the Boulevard Diderot site to 90% at the Rue de Tolbiac site. License plate numbers for all attempted measurements, whether successful or not, were submitted to the Ministry of the Interior in order to retrieve the vehicle technical information. As the

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

Site ID	Site name	Instrument ID	Measurement days	Total sampling time (hr)	Number total records	Number valid emission records	Number records with SIV info	Number valid emission records with SIV info
1	**Rue de Tolbiac**	7	11	265	36,483	32,955	35,196	32,277
2	**Boulevard Diderot**	8	22	453	131,420	107,756	125,534	105,404
3	**Avenue de Choisy**	7	11	246	50,678	43,674	48,949	42,630
		Total	**44**	**965**	**218,581**	**184,385**	**209,679**	**180,311**

records with SIV column shows, technical information was returned for 96% of the submitted plate numbers. Missing technical information could be due to partial reads of the plate number or lack of information on foreign vehicles. Finally, the last column shows the number of records in which both valid emissions data and vehicle technical information were available for the test vehicle. These data form the basis for the analysis presented in this report and totaled more than 180,000 records—one of the largest single-study sample sizes collected in a European remote sensing study to date. The majority of these data (58%) were collected at the Boulevard Diderot site, where an EDAR unit was deployed for the duration of the field study.

During the study, the two EDAR instruments collected data for a total of 965 hours. On average, about 190 valid emissions records were collected per hour per instrument. The most productive site was Boulevard Diderot (238 valid records/hour) followed by the Avenue de Choisy (178) and Rue de Tolbiac (124) sites. The instruments were operated continuously and collected data 24 hours a day, so these collection rates reflect both the more productive, higher traffic daytime sampling periods and overnight periods when there were fewer vehicles on the roads.

DATA PROCESSING AND ANALYSIS

At the conclusion of the data-collection phase of this project, HEAT provided the ICCT with a database containing all data collected during the summer 2018 vehicle remote sensing field study, including vehicle emissions data, operating conditions, and technical information, as well as supporting data, such as ambient weather conditions. Data processing and statistical analysis proceeded following standardized methods described in prior ICCT/TRUE publications.[11] In the following sections, we report the results of these analyses, beginning with a characterization of the sampled vehicle fleet. Detailed emissions results are then presented for passenger cars and light commercial vehicles, with a focus on NO_x and how these emissions vary by engine load and ambient conditions. Results are also presented for CO and PM emissions. Further assessment of the emissions from specific vehicle types, including L-category vehicles and buses, is considered in separate sections. Finally, emissions from the newest passenger cars, subject to RDE limits, are investigated.

CHARACTERISTICS OF THE SAMPLED FLEET

Figure 3 shows the characteristics of the fleet sampled in the TRUE Paris remote sensing study by vehicle type, fuel type, and Euro standard. It reflects all data records, including invalid emissions measurements and measurements where vehicle specifications could not be retrieved from the SIV registration database, so as to show a more complete picture of the vehicle fleet at the three sampling sites.

11 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. Dallmann et al., *Remote sensing of vehicle emissions in London.* Uwe Tietge, Yoann Bernard, John German, Rachel Muncrief, *A comparison of light-duty vehicle NOx emissions measured by remote sensing in Zurich and Europe,* (ICCT: Washington, DC, June 2019), https://www.theicct.org/sites/default/files/publications/ICCT_LDV_NOx_emissions_Zurich_20190626.pdf

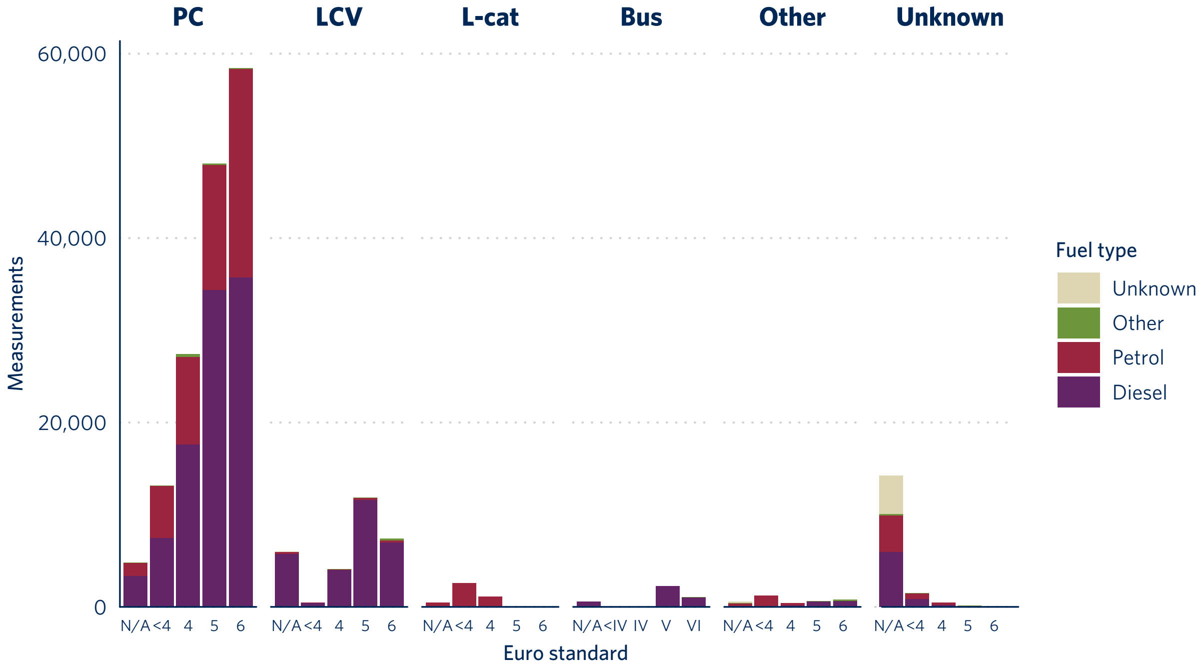


Figure 3. Number of remote sensing measurements by vehicle category, Euro standard, and fuel type.

The vehicle fleet at the three sampling locations consisted mainly of passenger cars and light commercial vehicles. These vehicle types account for 72% and 14% of total records, respectively. Other common vehicle types operating at the sampling sites include L-category vehicles and buses (transit and coach). While the total sample size for these vehicle types is much lower than for light-duty vehicles, it is still considerable—more than 4,000 records for L-category vehicles and almost 4,000 records for buses. Other vehicle types consist mostly of heavy goods vehicles. The vehicle category could not be determined for 8% of measurements.

The majority (64%) of passenger cars observed at the three sites were solely powered by diesel engines, with the remainder mostly powered by petrol engines (28%). Smaller numbers of hybrid electric (7%) and plug-in hybrid electric (<1%) vehicles were observed during the study. We were not able to detect the presence of zero-emission vehicles or hybrid vehicles operating exclusively on electric power, as the remote sensing system configuration used in the study relied on a detectable CO_2 signal in the exhaust plume to trigger the license plate camera.

Euro 5 and Euro 6 were the most common Euro standards for passenger cars, representing 38% and 32% of the total passenger car sample, respectively. Light commercial vehicles observed in the study were powered almost exclusively by diesel engines. Euro 5 is the most common Euro standard for this vehicle type. Information on Euro standard was missing in the SIV data for 20% of the light commercial vehicle sample.

All sampling sites were located within the Paris low-emission zone (LEZ), where older vehicles are banned from operating during certain periods of the day and days of the week. During the sampling period, pre-Euro 3 diesel cars and light commercial vehicles were restricted from 08:00–20:00 on weekdays. Pre-Euro IV diesel heavy-duty vehicles were restricted from 08:00–20:00 on all days. During the study, <1% of passenger cars at the sampling sites did not meet these minimum criteria, though some exemptions apply, for instance, to vehicles officially recognized as vintage cars. Access restrictions were tightened in July 2019, with further implementation phases scheduled for 2022, 2024, and 2030.

Figure 4 shows the share of vehicle types observed at each of the three sampling sites. The vehicle distribution at the Rue de Tolbiac and Avenue de Choisy sites was similar, with passenger cars and light commercial vehicles respectively making up 70% and 16%–17% of the fleet, on average. Relative to the other sites, passenger cars and buses made up a greater percentage of the fleet at the Boulevard Diderot site.

The measurement approach for the Paris study consisted of continuous sampling, allowing for investigation of how vehicle activity and fleet

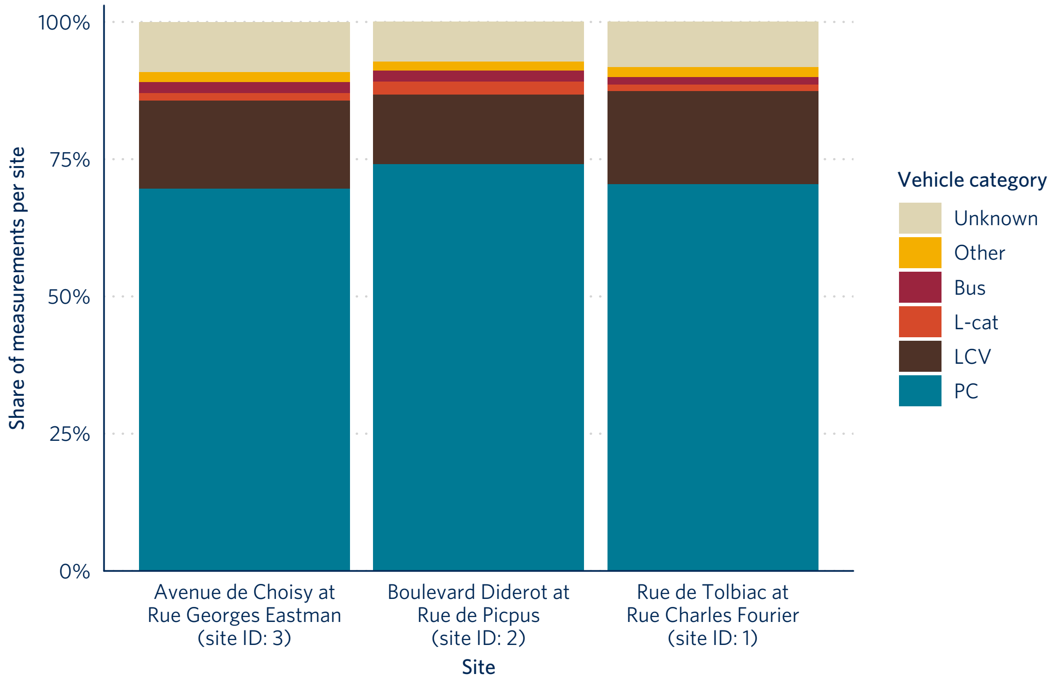


Figure 4. Share of vehicle categories by measurement site.

distribution changed over the course of the day. Figure 5 summarizes diurnal activity, with the top panels showing the study average number of measurements by time of day and the bottom panels showing the share of measurements by vehicle type. Results are split by weekdays and weekend days. On average, the sampling periods with the greatest number of measurements per hour occurred on weekdays between 10:00 and 19:00. This time period was also the most productive on weekend days, though the total number of measurements were lower relative to weekdays. This is largely due to decreases in light commercial vehicle traffic over the weekend. 44% of measurements in Paris were collected outside of the 07:00-19:00 time period or during weekends. This means that measuring around the clock and on weekends almost doubled the amount of measurements collected during the field study.

Some fleet composition effects were observed. For instance, the share of diesel passenger cars—particularly newer diesel cars—would have been underestimated if nighttime traffic had not been measured. The same is true for buses, which peaked around 5 a.m. during weekdays and weekends, possibly coinciding with their morning start from the depot.

Table 2 summarizes testing conditions and passenger car fleet characteristics in the Paris 2018 measurements for records with valid emissions data and SIV information. Paris data is compared against average results from remote sensing measurements made in other European cities, which have been compiled in the CONOX remote sensing database.[12] The table groups the data by fuel type and emission standard to facilitate comparison within and across subsamples 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 CO_2 emission values over the New European Driving Cycle (NEDC), ambient temperature at the time of measurement, and the power demand in terms of VSP.[13] Median values for Paris 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 Paris and CONOX data. The vehicle acceleration values presented here include gravitational forces from uphill driving to allow for better comparisons across datasets.

12 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-drivingemissions-from-diesel-passengers-cars-measured-by-remote-sensingand-as-compared-with-pems-and-chassis-dynamometer-measurementsconox-task-2-r.pdf

13 In France, information relative to vehicles' certified CO_2 emissions, Euro standard, and first day of registration are available in the registration document known as *carte grise*.

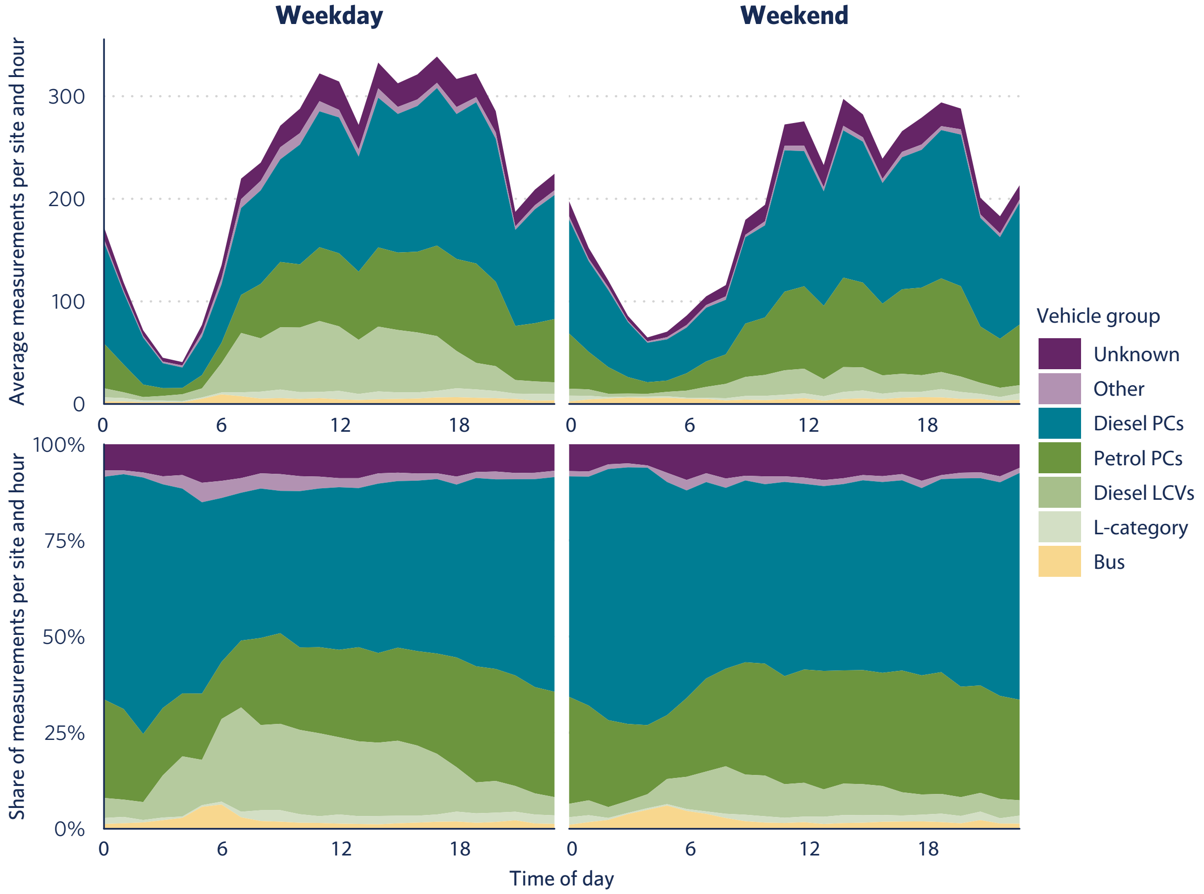


Figure 5. Average number of measurements per hour and site (top graph) and share of vehicle groups (bottom graph) by time of day and day of the week.

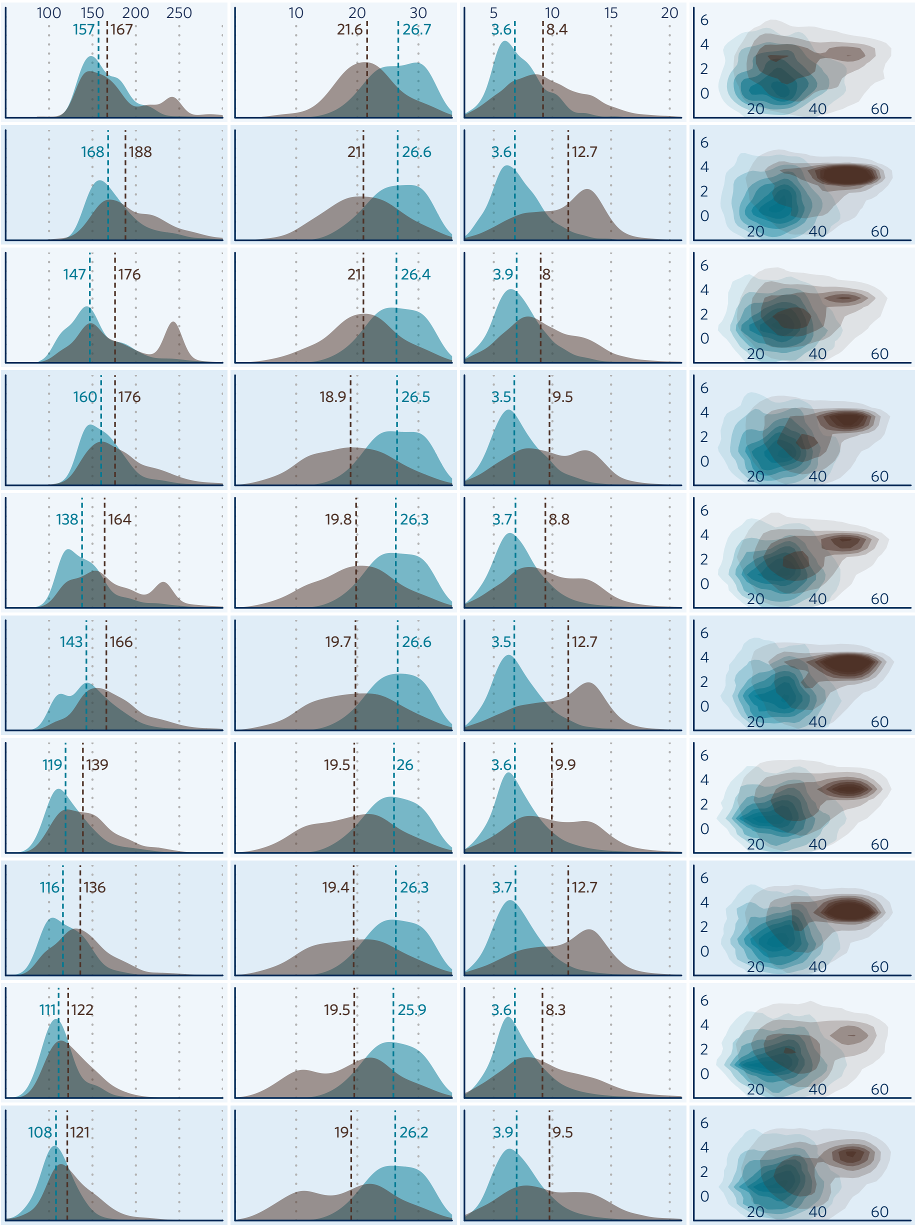
A full summary of ambient conditions during testing period appears in an appendix.

Relative to other European cities represented in the CONOX database, the Paris fleet contains a greater share of diesel cars. Diesel cars made up 64% of the Paris passenger car data, while accounting for 46% of total measurements in the CONOX database. Driving conditions at the Paris sampling sites tended to be milder, with lower average speed and acceleration values and less steep road grades than in the CONOX data. These factors contribute to the lower median VSP values for cars measured in Paris, which were 50% to 75% lower than for the CONOX data, depending on vehicle subsample. The median ambient temperature was 6–7 °C warmer for the Paris measurements relative to the CONOX data. Notably, a significant amount of the Paris data was collected at ambient temperatures above 30 °C, a range underrepresented in the CONOX database. Because the Paris study was more recent than the studies represented in the CONOX database, Euro 6 cars account for a greater percentage of passenger car measurements and vehicles of a given Euro standard tend to be older at the time of measurement for the Paris data. Finally, median certified CO_2 emission values are lower in the Paris data than in the CONOX data for all vehicle subsamples, a result likely explained by the fact that passenger cars in France tend to be smaller and lighter than those in the European countries represented in the CONOX database.[14]

14 European vehicle market statistics, 2018/2019. https://theicct.org/publications/european-vehicle-market-statistics-20182019

Table 2. *Summary of remote sensing testing conditions and passenger car fleet characteristics in Paris (blue) and 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	828 5,174	19 17	2.2% 4.4%	157 167	21.6 26.7	3.6 8.4	
Euro 2 Petrol	1,602 20,249	19 16	2.2% 5.5%	168 188	21 26.6	3.6 12.7	
Euro 3 Diesel	5,569 31,657	15 12	2.2% 4.4%	147 176	21 26.4	3.9 8	
Euro 3 Petrol	3,239 43,154	15 13	2.2% 4.4%	160 176	18.9 26.5	3.5 9.5	
Euro 4 Diesel	14,553 68,420	10 8	2.2% 4.4%	138 164	19.8 26.3	3.7 8.8	
Euro 4 Petrol	7,714 98,313	11 9	2.2% 5.5%	143 166	19.7 26.6	3.5 12.7	
Euro 5 Diesel	31,329 91,720	5 4	2.2% 4.4%	119 139	19.5 26	3.6 9.9	
Euro 5 Petrol	12,250 79,246	5 4	2.2% 5.5%	116 136	19.4 26.3	3.7 12.7	
Euro 6 Diesel	32,485 38,987	2 1	2.2% 3.3%	111 122	19.5 25.9	3.6 8.3	
Euro 6 Petrol	20,345 30,839	2 2	2.2% 4.4%	108 121	19 26.2	3.9 9.5	



LIGHT-DUTY VEHICLE EMISSIONS

In this section, we present emissions results for light-duty vehicles. The primary focus is on passenger cars, the vehicle type most prevalent in the Paris fleet and for which we have collected the most remote sensing data. We consider NO_x, CO, and PM emissions. HC emissions were also measured during the study and will be the focus of a future publication. NO_x and CO emissions results are also presented in this section for light commercial vehicles.

NITROGEN OXIDES

Figure 6 presents average fuel-specific NO_x emissions of passenger cars and light commercial vehicles in grams NO_x per kilogram fuel (g/kg) for the Paris data compared against results from the CONOX dataset. Emissions trends by Euro standard for the Paris data are consistent with those measured in other European cities and reinforce previous findings regarding high in-use emissions from light-duty diesel vehicles. Petrol passenger car emission rates have decreased consistently with the implementation of more stringent regulatory standards.[15] The average fuel-specific emission rate for Euro 6 petrol cars measured in Paris is 81% lower than the emission rate for the oldest (Euro 2) petrol cars. Emission rates of Euro 5 and Euro 6 petrol light commercial vehicles are in line with those of similar age petrol passenger cars, though there are limited data available for these vehicles.

In contrast to the downward trend observed for NO_x emissions from petrol cars, little improvement is seen in average real-world fuel-specific emissions from Euro 2–Euro 5 diesel passenger cars. The NO_x emissions performance of the average Euro 6 diesel car is improved somewhat compared to previous Euro standards, though it remains poor relative to similar age petrol cars. For the Paris data, average fuel-specific NO_x emissions from Euro 6 diesel cars were almost 5 times those of Euro 6 petrol cars. Emissions trends

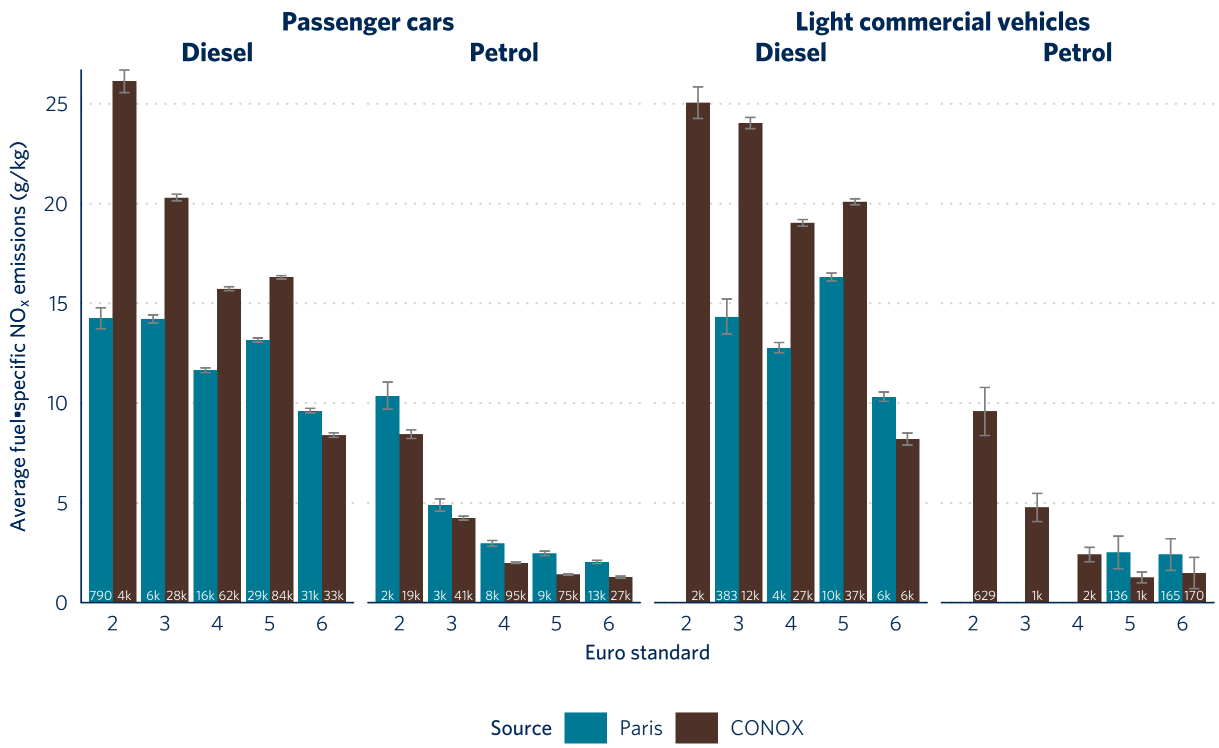


Figure 6. Average fuel-specific NO_x emissions by fuel type and Euro standard for passenger cars and light commercial vehicles in Paris (blue) and CONOX (brown).
Notes: The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean. Results are not shown for subgroups with less than 100 total measurements.

15 Note that petrol Euro 5 and Euro 6 standards are identical for NO_x, so no decrease is expected in real world emissions from Euro 5 to Euro 6.

by Euro standard for diesel light commercial vehicles were similar to those for diesel passenger cars. Notably, among the light-duty vehicle subgroups in the Paris data, fuel-specific NO_x emissions were, on average, highest for Euro 5 diesel light commercial vehicles.

Comparisons of Paris data and CONOX data varied by vehicle subgroup. Relative to the CONOX data, the average fuel-specific NO_x emissions for passenger cars measured in Paris tended to be lower for Euro 2–Euro 5 diesel vehicles, and greater for Euro 6 diesel vehicles and for petrol vehicles of all Euro standards. There are many factors that may affect the observed variance in average NO_x emissions between the two datasets. These include, but are not limited to, fleet composition, driving conditions, ambient conditions, and remote sensing instrumentation. Oftentimes, the influence of each of these factors can be difficult to isolate.

The remote sensing instrument used in the Paris study differs from the systems used in the studies that make up the CONOX database, which employed various iterations of cross-road remote sensing instruments with similar technology and measurement approach. A detailed assessment of remote sensing instrumentation is beyond the scope of this report. The results from previous evaluations of the performance of the EDAR system[16] and preliminary comparisons with commercial cross-road systems[17] lead us to believe that instrumental differences are small and are not the key driver of the disparity in Paris and CONOX NO_x emissions results. However, there remains a need for more comprehensive investigation of the comparative performance of remote sensing systems being used today.

Other factors that likely influence differences in Paris and CONOX NO_x emissions results include vehicle operating conditions and the prevailing ambient conditions when measurements were made. As noted earlier, driving conditions in the Paris study were, on average, milder than those observed in other European remote sensing studies that make up the CONOX database. This is reflected in the much lower median VSP values for the Paris study as compared to the CONOX data shown in Table 2.

16 Karl Ropkins et al., "Evaluation of EDAR vehicle emissions remote sensing technology," *Science of the Total Environment* 609 (2017): 1464–1474, http://dx.doi.org/10.1016/j.scitotenv.2017.07.137

17 European Commission Joint Research Centre, *Assessment of RSD measurement performance against reference vehicles and PEMS measurements: Potential for Euro 6 in-service vehicle emissions screening,* https://www.theicct.org/sites/default/files/EC_JRC_Remote_Sensing_09_2017_V5_Final.pdf

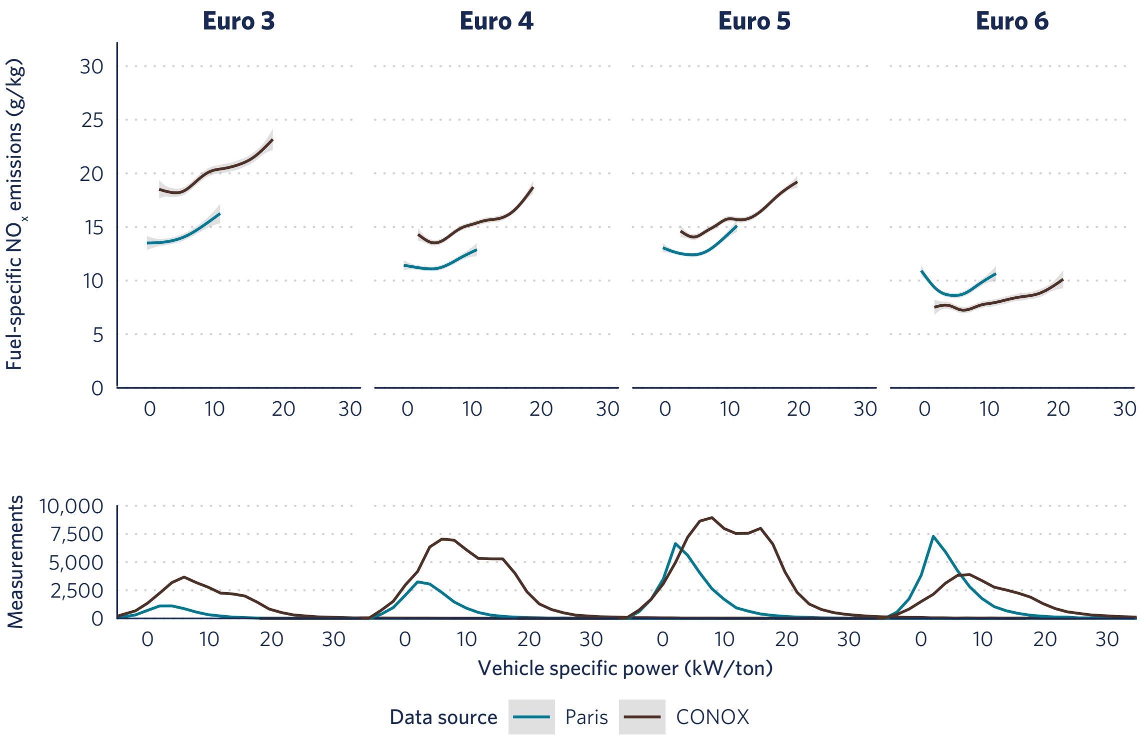


Figure 7. VSP distribution (bottom panel) and fuel-specific NO_x emissions of diesel passenger cars in Paris (blue) and CONOX (brown) as a function of VSP (top panel).

Notes: Relationship represented using generalized additive models. The VSP range in the top panel is truncated to the 10th–90th percentile.

Figure 7 uses generalized additive models to further illustrate the extent to which operating conditions can explain the differences in the Paris and CONOX NO_x emissions results for diesel passenger cars. The top panel shows the relationship between fuel-specific NO_x emissions and VSP for Euro 3 to Euro 6 passenger cars for Paris 2018 and CONOX data, while the bottom panel shows the VSP distribution for each dataset by Euro standard. The Paris and CONOX data show similar trends, with NO_x emissions increasing with increasing VSP; however, there are notable differences in model results at common VSP values across all Euro standards. These findings indicate that while VSP likely explains some of the difference between the Paris and CONOX NO_x emissions, alone it cannot explain all of the variance in average fuel-specific diesel NO_x emissions between the Paris and CONOX datasets.

In addition to engine load, ambient temperature can influence NO_x emissions from diesel cars. Previous analysis of European diesel passenger car remote sensing data has demonstrated a strong dependence of fuel-specific NO_x emissions on colder ambient temperatures.[18] These studies show an increase in fuel-specific NO_x emissions from diesel cars at lower temperatures, especially below 15° C, in particular for pre-Euro 6 vehicles. This is in contrast to NO_x emissions from gasoline cars, where the researchers found little dependence on ambient temperatures.

The Paris dataset extends this research through the addition of measurements made at warmer temperatures, above 30 °C, which are not currently well represented in remote sensing databases (see Table 2). Approximately 30% of the Paris data were collected at temperatures greater than 30 °C, with a maximum of 35°C, providing a substantial sample size from which to draw initial conclusions regarding the effect of warmer temperatures on diesel car NO_x emissions.

Figure 8 presents the NO_x/VSP relationship for diesel passenger cars measured during Paris 2018 study for two different ambient temperature ranges. There are

18 Åke Sjödin et al., "On-road emission performance of late model diesel and gasoline vehicles as measured by remote sensing" (IVL Swedish Environmental Research Institute, June 2017), https://www.ivl.se/download/18.4 49b1e1115c7dca013adad3/1498742160291/B2281.pdf. Stuart Kenneth Grange et al., "Strong temperature dependence for light-duty diesel vehicle NO emissions," *Environmental Science & Technology* 53, 11 (2019): 6587-6596, DOI:10.1021/acs.est.9b01024

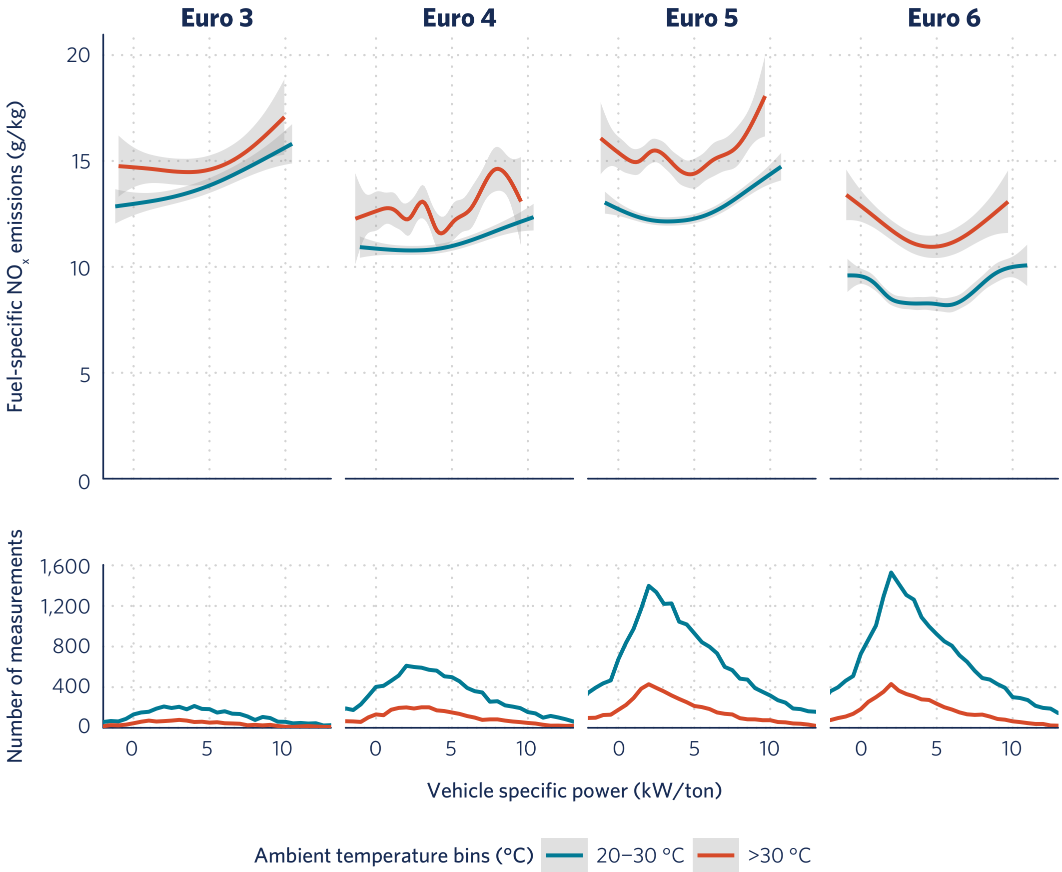


Figure 8. VSP distribution (bottom panel) and fuel-specific NOx emissions of diesel passenger cars as a function of VSP and ambient temperature (top panel) in Paris.

Notes: Relationship represented using generalized additive models based on Paris 2018 dataset. The VSP range in the top panel is truncated to the 10th–90th percentile.

clear differences in fuel-specific NO_x emissions among the temperature bins, with the highest emissions measured during periods where ambient temperatures were ≥30 °C. For similar operating conditions, NO_x emissions at temperatures ≥30 °C were about 2.4 g/kg (19%) greater than emissions at temperatures between 20 °C and 30 °C for Euro 5 diesel cars, and 2.7 g/kg (29%) greater for Euro 6 diesel cars. For gasoline cars, there was no strong indication of the impact of ambient temperature above 30 °C on NO_x emissions.

It is important to note that warmer temperature measurements were made in conditions outside of the NEDC type-approval testing temperature range of 20–30 °C. Across the study, the greatest number of measurements were made at ambient temperatures between 20 °C and 30 °C. Results for these conditions thus have the greatest influence over average NO_x emission results reported for the full study period, although warmer temperatures increase ozone formation so NO_x emissions at warmer temperatures have larger health impacts.

We are not aware of any valid engineering reasons why higher ambient temperatures in this range should have the level of impact on diesel NO_x emissions observed in this study. The effect of temperatures between 30 °C and 40 °C on the performance of diesel engine and exhaust aftertreatment systems is small. The higher NO_x emissions from diesel cars observed in this study suggest that manufacturers are employing deliberate strategies to reduce the efficiency of NO_x control systems at warmer temperatures outside the laboratory certification test range. That NO_x emissions from Euro 6 diesel cars decreased between 20 °C and 30 °C compared to earlier standards, but did not decrease significantly compared with Euro 4 cars—which, in contrast to Euro 6, are not equipped with NO_x aftertreatment technology—at temperatures above 30 °C and

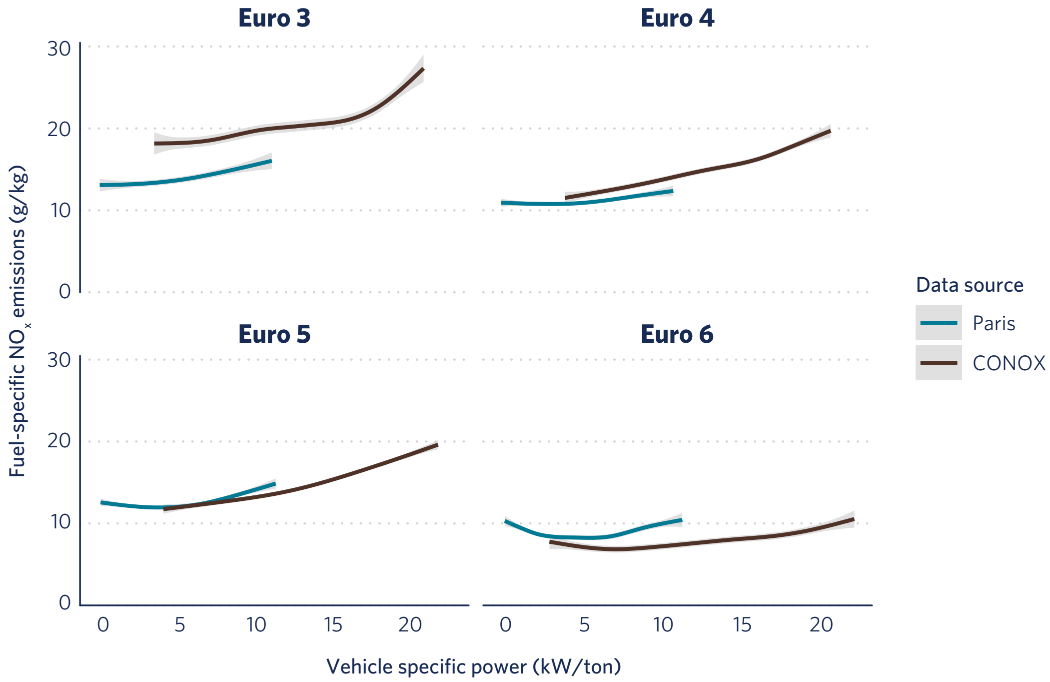


Figure 9. Fuel-specific NO_x emissions of diesel passenger cars as a function of VSP in Paris (blue) and CONOX (brown) filtered for ambient temperatures between 20 °C and 30 °C.
Notes: Relationship represented using generalized additive models based on Paris 2018 and CONOX datasets.

therefore outside the official ambient temperature test window, tends to support that hypothesis.

This observation, sharply rising NO_x emissions in hot weather, is significant. Paris, like other cities around the world, faces higher ambient temperature extremes and longer periods of summer high temperatures due to global warming. Further research is needed to investigate the causes of high NO_x emissions from diesel cars at temperatures above 30 °C and the potential impacts of elevated emissions at higher temperatures on air quality.

Returning to the comparison of Paris and CONOX results for diesel passenger car NO_x emissions, Figure 9 presents the relationship of fuel-specific emissions and VSP for the subset of measurements made at ambient temperatures between 20 °C and 30 °C. For these conditions, results are similar, and trends align well for Euro 4–Euro 6 cars. The variance in the two datasets for Euro 3 diesel car NO_x emissions is not entirely explained by engine load and ambient temperatures, suggesting that other factors may be contributing to the differences observed for this subgroup. These findings suggest Paris and CONOX results are, in general, comparable for similar testing conditions. The lower ambient temperature conditions and higher power demand of the CONOX data likely contribute to higher average NO_x emissions observed for diesel cars in the CONOX data.[19]

19 Tietge et al., *A comparison of light-duty vehicle NO_x emissions.*

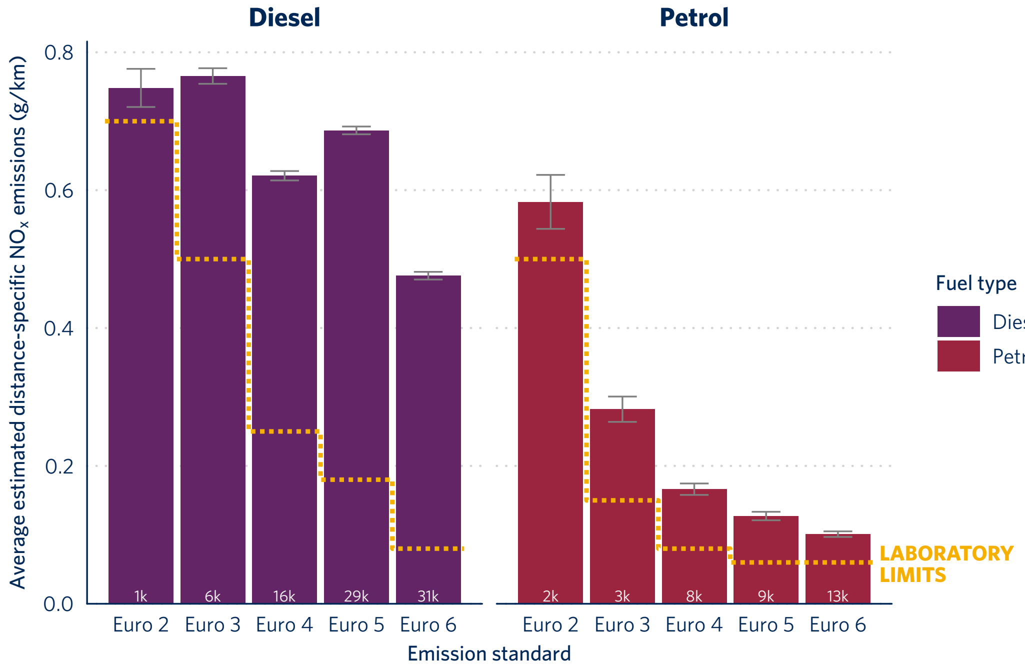


Figure 10. Estimated average distance-specific NO_x emissions by fuel type and Euro standard for passenger cars measured in Paris in 2018.
Notes: The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean.

Distance-specific NO_x emissions in units of grams per kilometer can be estimated from remote sensing fuel-specific emission data, along with estimates of the average real-world fuel consumption of a vehicle model or group of models.[20] Figure 10 presents estimates of the distance-specific NO_x emissions of passenger cars in the Paris dataset and compares against laboratory type-approval limits. Distance-specific NO_x emission trends by Euro standard for diesel and petrol cars in Paris are similar to fuel-specific emission trends presented in Figure 6. For diesel cars, improvements in distance-specific NO_x emissions stagnate with vehicles certified to Euro 2 through Euro 5 standards, then jump for Euro 6 cars. Despite the improvement seen with Euro 6, estimated mean distance-specific emissions for Euro 6 diesel cars in the Paris dataset, 0.48 g/km, are 6 times the laboratory emission limit.

On average, NO_x emissions from Euro 6 diesel cars in Paris are elevated relative to most petrol cars measured in the study. The mean distance-specific NO_x emissions of Euro 6 diesel cars are 4.8 times the emissions of Euro 6 petrol cars, and only 18% lower than the emissions of the oldest (Euro 2) petrol cars for which we have data. Euro 6 standards have been introduced in stages, and the newest Euro 6 cars observed in the Paris study are subject to RDE type-approval test limits. A more detailed description of the real-world emissions from Euro 6 cars is included in a separate analysis presented later in this report.

20 Bernard et al., *Determination of real-world emissions.*

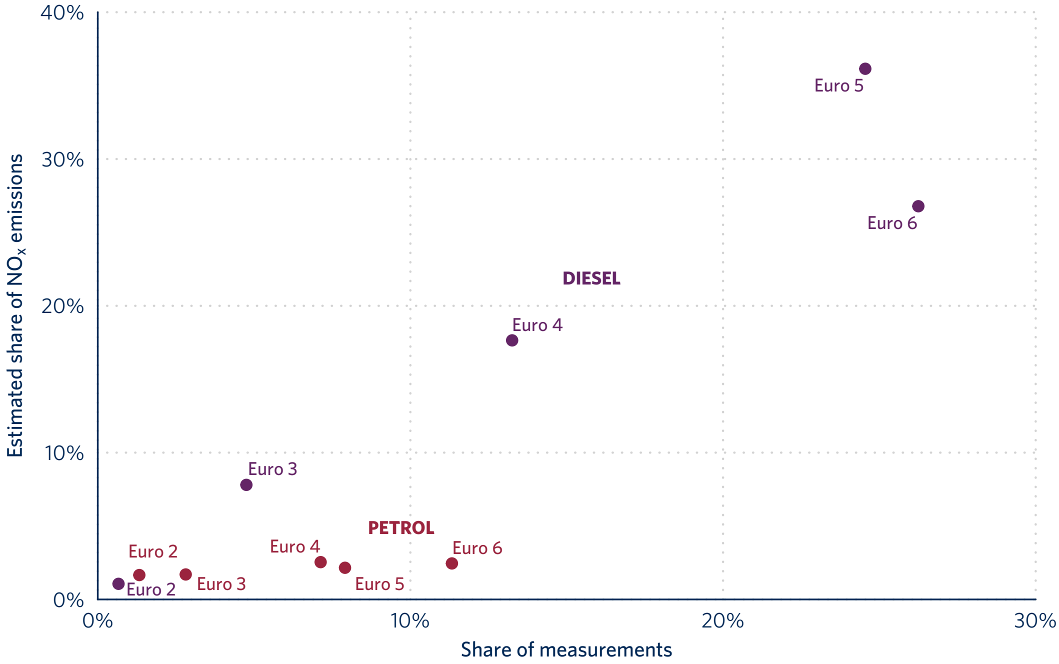


Figure 11. Estimated share of annual NO_x emissions from passenger cars and respective share of remote sensing measurements in Paris, differentiated by Euro standard and fuel type.

These findings can be applied to investigate the level of NO_x emissions control that could be achieved by tightening access restrictions for the Paris LEZ. For example, while the passenger vehicle subgroup with the highest average distance-specific NO_x emission rate, Euro 3 diesel cars, will be subject to access restrictions beginning 4 July 2019, restrictions for other high-emitting vehicles groups like Euro 4 and 5 diesel cars will not enter into force until 2022 and 2024.

Figure 11 estimates the fraction of on-road NO_x emissions from passenger cars measured in Paris by fuel type and emissions standard. Here, we use the share of remote sensing measurements as a proxy for citywide in-use fleet composition. The figure shows that Euro 5 and older diesel cars made up 43% of the passenger vehicle fleet but were responsible for 63% of NO_x emissions. Euro 5 diesel cars were the highest emitting subgroup and are estimated to account for 36% of passenger car NO_x emissions in Paris. Euro 4 to Euro 6 petrol cars made up about the same share of total measurements as Euro 6 diesel cars. However, the share of NO_x emissions from Euro 6 diesel cars is estimated to be much greater than the combined share from Euro 4 to Euro 6 petrols (27% vs. 9%).

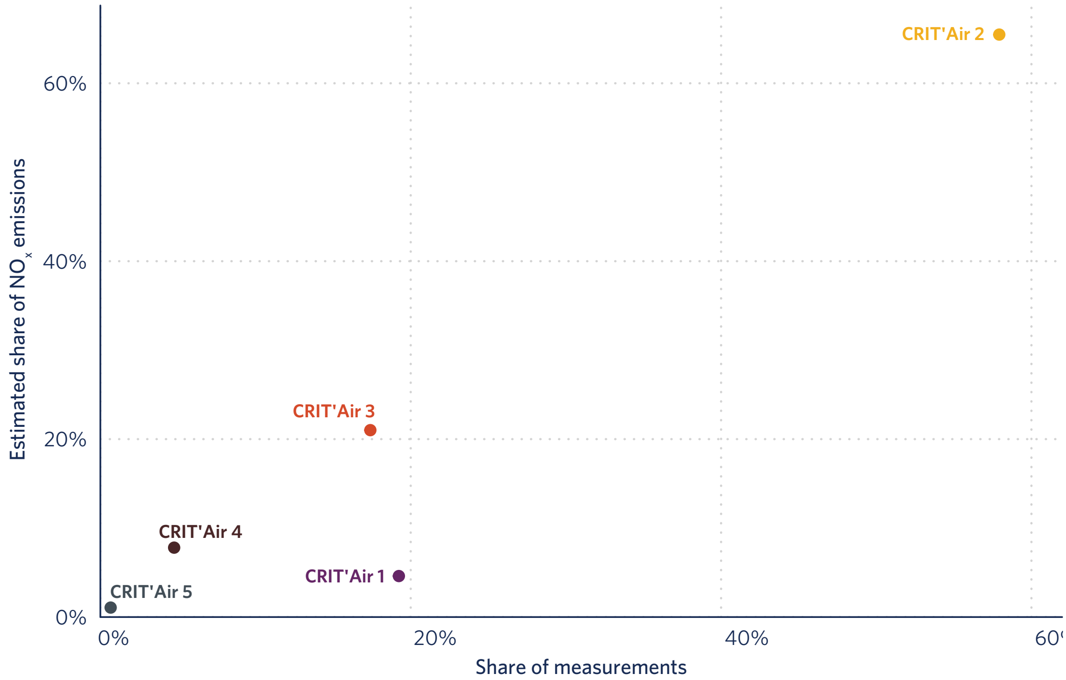


Figure 12. Estimated share of annual NO_x emissions from passenger cars and respective share of remote sensing measurements in Paris differentiated by Crit'Air classification. Vehicles ineligible for Crit'Air classification represented around 0.03% of measurements and of total NO_x and are not presented in this figure.

Figure 12 shows the results of a similar analysis of the share of passenger car NO_x emissions by vehicle subgroup. In this case, passenger cars are grouped by Crit'Air classification, a program introduced in France to support the development and enforcement of low-emission zones. Crit'Air was introduced on 1 July 2016 by the French ministry of environment and divides vehicles into six color-designated categories according to fuel type, Euro standard (or, if not available, by date of first registration),[21] and propulsion energy.[22] The system promotes first the use of zero-emission vehicles (green sticker), and second vehicles with low emissions of NO_x and PM (Crit'Air 1). Older and higher-emitting vehicles qualify for Crit'Air 2 through 5 classification, with the oldest vehicles ineligible for a Crit'Air label.

Cities in France can make use of the Crit'Air system to design LEZ policy and build timelines for enforcing vehicle restrictions. The first restricted traffic zone was set up in Paris in September 2015. Initially, access was prohibited for buses and heavy goods vehicles registered before October 2001. In July 2016, Paris adopted the Crit'Air system, starting with the ban of vehicles ineligible for a Crit'Air label. A year later, access restrictions were extended to Crit'Air 5 vehicles. In July 2019 the Paris LEZ was further tightened to exclude Crit'Air 4 vehicles.

During the Paris remote sensing campaign, passenger cars without Crit'Air labels accounted for less than 0.03% of total passenger cars, and Crit'Air 5 cars made up less than 1% of the passenger car sample. Our estimates for Paris suggest that Crit'Air 4 passenger cars, whose access is restricted since July 2019, contributed to around 8% of total NO_x emissions. Crit'Air 3 vehicles (Euro 4 diesels, Euro 2 and Euro 3 petrols), which will be subject to access restrictions in 2022, were responsible for 21% of passenger car NO_x emissions at the time of the field study. Crit'Air 2 vehicles (Euro 5 and Euro 6 diesels, Euro 4 petrols) accounted for 58% of the measured passenger car fleet and were responsible for 65% of total NO_x emissions. The elevated NO_x share from Crit'Air 2 vehicles is due primarily to Euro 5 and Euro 6 diesel cars, which account for 96% of the NO_x emissions from this Crit'Air class. Although they emit large amounts of NO_x, Crit'Air 2 vehicles exhibit low

21 The date of first registration can be used as a proxy of the Euro standard by comparing it to the date when all types of vehicles must meet a new standard. In some cases, this can lead to an incorrect standard identification. In particular, a limited number of vehicles produced before that date can benefit from an end-of-series derogation that would allow their registration at a later date.

22 Crit'Air classification of vehicles. https://www.certificat-air.gouv.fr/docs/tableaux_classement.pdf

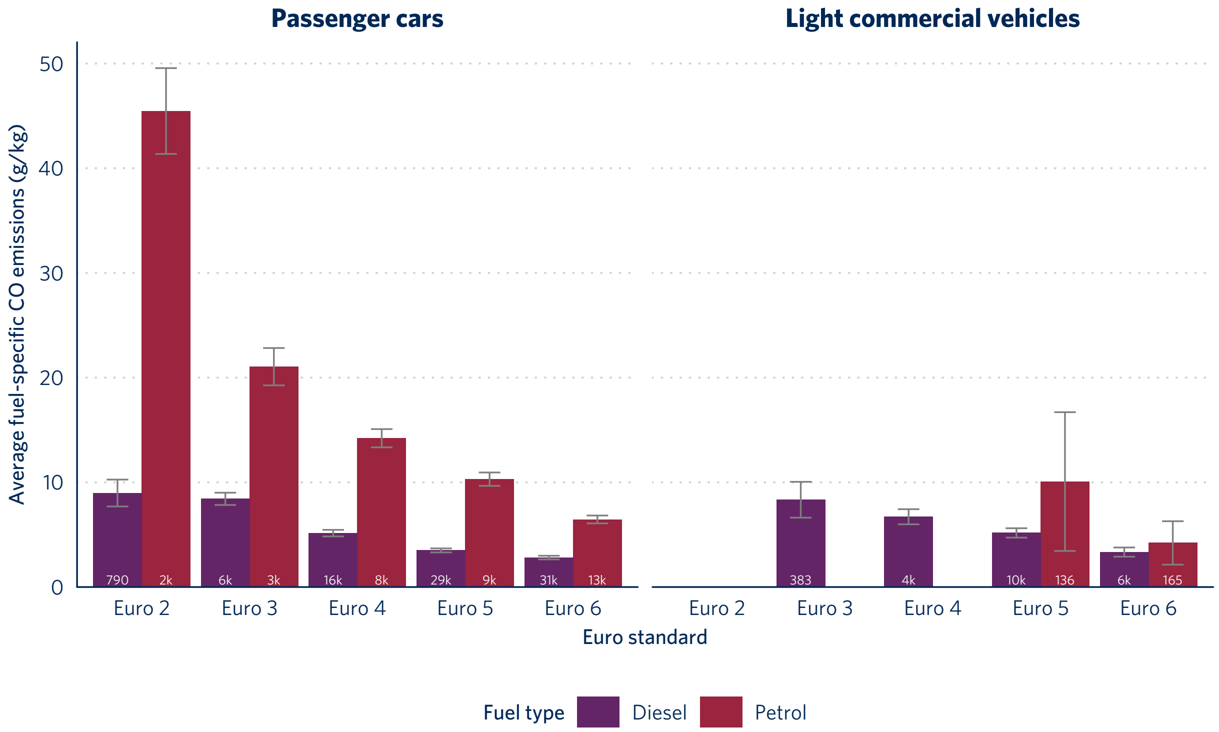


Figure 13. Average fuel-specific CO emissions by fuel type and Euro standard for passenger cars and light commercial vehicles.
Notes: The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean. Results are not shown for subgroups with less than 100 total measurements.

PM emissions (see a later section of this paper). Under current policies, these vehicles will be allowed to operate on Paris streets without restriction until 2024.

The Paris LEZ and its effects on NO_x emissions will be explored in a companion publication, now in preparation, that will use remote sensing emissions data, along with projections of the evolution of the Paris passenger car fleet to evaluate the potential impact of tightened LEZ requirements scheduled for 2022, 2024, and 2030 on fleet-average NO_x emission rates.

CARBON MONOXIDE

Paris is in attainment with air quality objectives for ambient CO concentrations. However, vehicular CO emissions should continue to be controlled to maintain this compliance and because CO is also a precursor to tropospheric ozone formation.[23] Figure 13 presents average fuel-specific CO emissions of light-duty vehicles in grams CO per kilogram fuel for the 2018 Paris data. The CO emissions from diesel passenger cars and light commercial vehicles are significantly lower than those from petrol vehicles across all Euro standards. Diesel engines operate in lean combustion conditions (i.e., with excess oxygen in the air-fuel mixture) almost all of the time, which promotes more complete fuel oxidation through combustion and catalyst conversion and, therefore, lower CO emissions. That said, these results do show improvement in the CO emissions performance of all cars and light commercial vehicles. For example, the newest diesel passenger cars (Euro 6) emit 69% less CO per kilogram of fuel combusted than the oldest (Euro 2) diesel cars observed in the study. The CO emissions from petrol cars have improved to an even greater extent with the implementation of more stringent emission standards. The average fuel-specific CO emissions for Euro 6 petrol passenger cars is 6.5 g/kg, which is 86% lower than the average emission factor measured for Euro 2 cars.

Figure 14 presents mean, median, and 90th percentile distance-specific CO emissions of petrol passenger cars measured in Paris as a function of vehicle age. Mean emissions were estimated using generalized additive models; median and 90th percentile emissions were estimated using quantile regression. The figure shows increasing CO emissions with vehicle age for petrol passenger cars across all Euro standards. This trend is an indication of the deterioration and decreased efficiency of exhaust aftertreatment control systems over time and is consistent with findings from the TRUE London remote sensing study.[24] For Euro 3, Euro 5, and Euro 6 vehicles, mean and median CO emission values meet respective emission limits across all vehicle ages. Median CO emission values remain within limits across all vehicle ages for Euro 4 vehicles, though mean values exceed limits after 13 years and seem to rapidly increase for older vehicles. Euro 4 petrol cars are eligible for Crit'Air 2 classification and will not face access restrictions until January 2024. At that date, these vehicles will be on average 17 years old, and at best 13 years old. The accelerated deterioration of

23 European Environment Agency, "Air quality in Europe — 2018 report," EEA Air Quality Report No 12/2018, https://www.eea.europa.eu//publications/air-quality-in-europe-2018

24 Dallmann et al., *Remote sensing of motor vehicle emissions in London.*

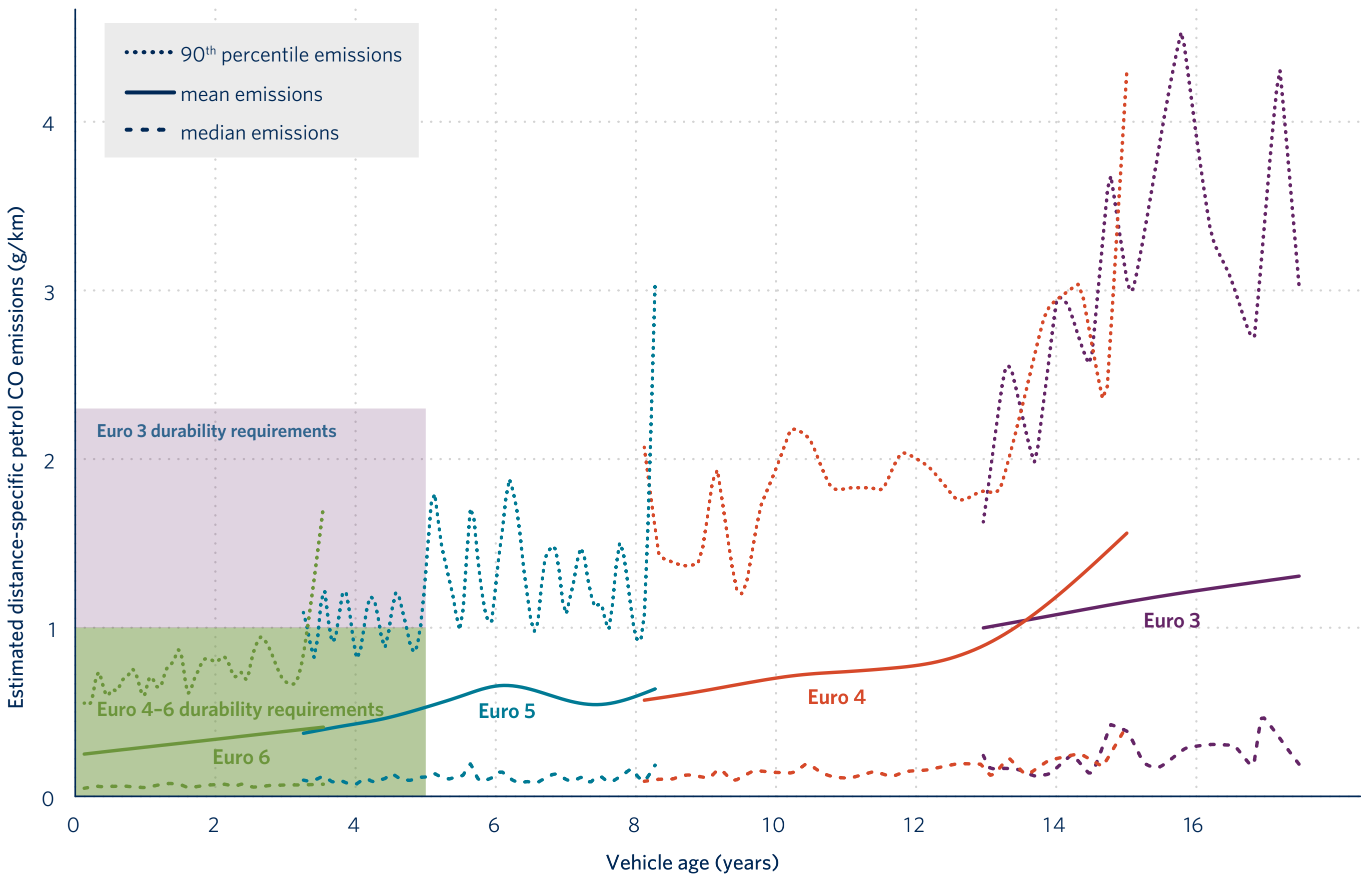


Figure 14. Median, mean, and 90th percentile estimated distance-specific CO emissions per Euro standard of petrol passenger cars over vehicle age.
Notes: The rectangular grid represents durability requirements for Euro 3-Euro 6. The age ranges are truncated, from 5th to 95th percentile, for each Euro standard.

CO emissions beyond that age suggests there would be benefits in replacing them earlier with newer vehicles.

PARTICULATE MATTER

Like other remote sensing instruments, the EDAR system employs a method whereby the interaction of light with particles in a vehicle exhaust plume is used to measure particulate matter emissions. The EDAR unit uses a laser light source, which is swept through the exhaust plume of the vehicle targeted for emissions measurement. As the light passes through the plume, it is absorbed and scattered by particles. These interactions are governed by particulate matter properties (e.g., particle size distribution and chemical composition) and the wavelength of the light source. The EDAR instrument measures light extinction, or the total amount of light absorbed or scattered by particles, at two wavelengths in order to isolate the exhaust PM signal from particles present in the background air. A scaling factor is applied to the light extinction measurement and PM emissions results are reported in units of nanomoles PM per mole CO_2 (nmol/mol). All remote sensing systems, regardless of design and manufacture, measure PM optically, so results are not directly comparable to PM emissions metrics like particulate mass or particle number typical of regulatory emissions testing. Further work is needed to investigate the correlation of remote sensing PM results with these established metrics.

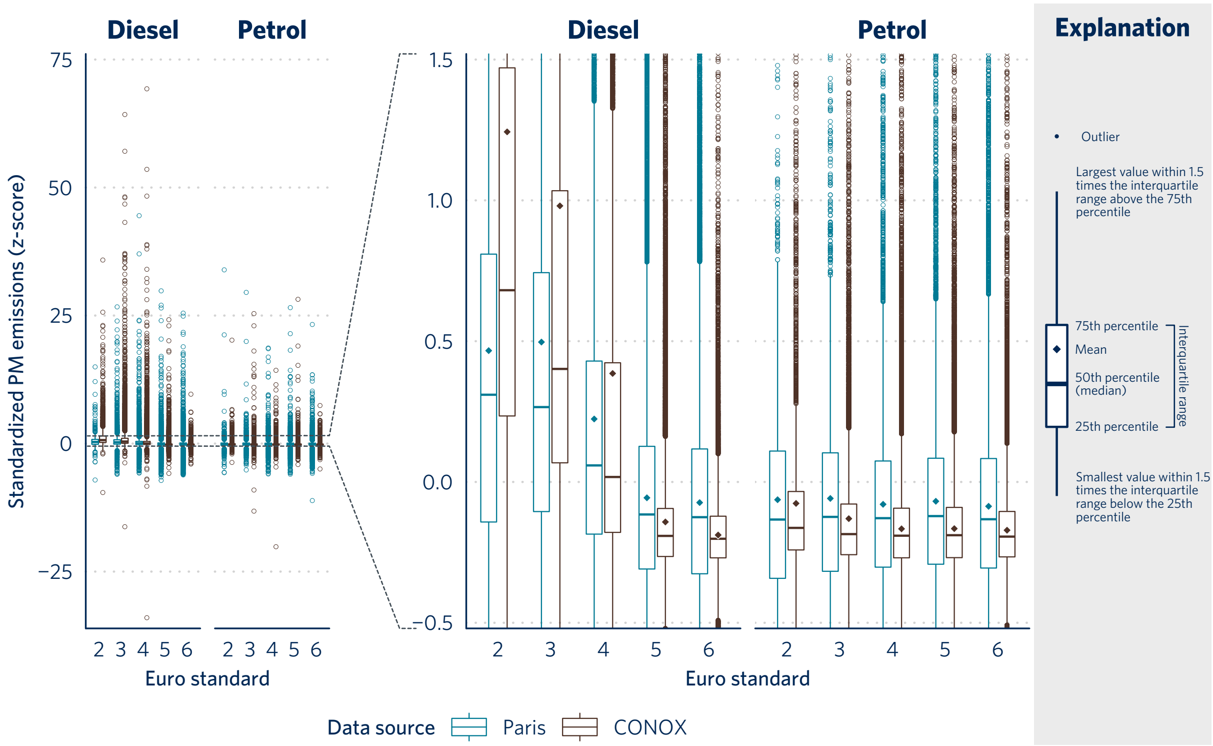


Figure 15. Boxplot of fuel-specific (CONOX) and CO_2-specific (Paris) PM emissions of passenger cars by Euro standard and fuel type.
Notes: For both Paris and CONOX datasets, standardized values (z-scores) were calculated per data source.

Figure 15 presents PM emissions results for passenger cars by Euro standard and fuel type for the Paris and CONOX data sets. Because the EDAR instrument reports PM emissions in different units than instruments used for CONOX data collection, results have been normalized by calculating the standard score (z-score) of each measurement relative to its data source (Paris and CONOX separately). This method allows for comparisons of trends in the central tendency between the datasets, while maintaining some indication of the dispersion of the PM data. A limitation of the normalization per data source is that results are implicitly weighted by the fleet composition, and the weighting may differ between the CONOX and the Paris data where only the EDAR instrument was used.

Overall, the Paris PM data show trends similar to those observed in the CONOX data. The PM emissions of petrol cars have been historically low, with little difference in mean normalized remote sensing emission results for Euro 2 to Euro 6 cars. In contrast, PM emissions from diesel cars have, on average, declined over time, coinciding with the introduction of more stringent emission limits and the application of aftertreatment technologies to control PM emissions. Beginning with Euro 5 cars, where diesel particulate filters were universally applied to meet PM mass and particle number emission limits, significant improvement is seen in the mean normalized PM emissions, with emissions from Euro 5 and Euro 6 diesel cars in line with those from petrol cars. This tends to explain why diesel Euro 5 and Euro 6 are grouped in Crit'Air 2. The dispersion of the Paris PM data is consistent with data collected using other remote sensing instruments.

L-CATEGORY VEHICLE EMISSIONS

L-category vehicles encompass a diverse set of vehicle types, including mopeds, motorcycles, tricycles, and quadricycles (Table 3). In Paris, these vehicles make up a small percentage of the on-road kilometers traveled but have a disproportionate impact on emissions. For example, the 2015 Paris region emission inventory estimates that motorized 2-wheeled vehicles account for only 7% vehicle activity as measured by kilometers traveled but are responsible for 46% of road transport non-methane HC emissions.[25]

Historically, the stringency of emission standards for L-category vehicles has lagged behind other on-road vehicle types. Table 4 shows a comparison of Euro standards for petrol L-category and passenger vehicles. The current standard for L-category vehicles, Euro 4, was implemented between 2016 and 2018, 11–12 years after the introduction of Euro 4 standards for passenger cars. Furthermore, g/km emission limits for Euro 4 L-category vehicles are set at higher levels than limits for Euro 6 petrol passenger cars. Euro 5 standards have been adopted for L-category vehicles and will come online 1 January 2020 for most new vehicle types and 1 January 2021 for most existing vehicles types.

At the time of this study, L-category vehicles first registered from June 2000 were allowed to operate without restriction in the Paris LEZ. Beginning 4 July 2019, LEZ requirements were tightened, and pre-Euro 2 L-category vehicles are currently not allowed in the LEZ between 08:00 and 20:00 on weekdays. Future strengthening of the LEZ requirements will extend access restrictions to pre-Euro 3 vehicles in 2022 and pre-Euro 4 vehicles in 2024. Euro 4 L-category vehicles will be allowed to circulate freely in Paris until 2030, when all petrol and diesel vehicles will be subject to access restrictions.

Real-world emissions from L-category vehicles have not been studied to the same extent as other vehicle types. The remote sensing data collected in Paris provides an opportunity to further the understanding of the emissions from this source category. In total, the Paris study yielded 3,455 valid emissions records for L-category vehicles. Figure 16 shows the number of valid emission measurements by vehicle subcategory and Euro standard. Also shown are the total number of attempted emissions measurements of L-category vehicles that were unsuccessful and deemed invalid. Relative to other vehicle types, the share of invalid measurements is much higher for L-category vehicles. Mopeds and smaller motorcycles tend to drive in close proximity to other vehicles on the road and their emissions plume is oftentimes not clearly distinguishable. Also, the smaller engines used in these vehicles result in a smaller plume signal relative to vehicles with larger engines.

Table 3. Type-L vehicle categories and descriptions.

EU Category	L1e-B	L3e-A1	L3e-A2	L3e-A3	L5e-A
Description	Two-wheel moped	Low-performance motorcycle	Medium-performance motorcycle	High-performance motorcycle	Tricycle
Power	≤ 4 kW	≤ 11 kW	≤ 35 kW	> 35 kW	—
Speed	≤ 45 km/h	—	—	—	—
Power to mass ratio	—	≤ 0.1 kW/kg	≤ 0.2 kW/kg	—	—
Application	Mainly designed for passenger transport, often equipped with engine under 50cc	Mainly designed for passenger transport, often equipped with engine under 125cc	Mainly designed for passenger transport	Mainly designed for passenger transport	Mainly designed for passenger transport

25 Airparif, *Bilan des émissions atmosphériques en Île-de-France, Année 2015—version décembre 2018,* April 2019, https://www.airparif.asso.fr/_pdf/publications/inventaire_emissions_idf_2015_20190329.pdf

Table 4. Comparison of emission standards for petrol L-category and passenger vehicles.

Euro standard	Euro 4			Euro 6
EU Category "description" Max speed category (km/h)	L1e-B "moped"	L3e/L5e-A "motorcycles/tricycles" <130 / ≥130	M1 "passenger cars"	M1 "passenger cars"
Date for new type of vehicles	1-Jan-17	1-Jan-16	1-Jan-05	1-Sep-14
Date for all existing types	1-Jan-18	1-Jan-17	1-Jan-06	1-Sep-15
NO_x (g/km)	0.17	0.07/0.09	0.08	0.06
THC (g/km)	0.63	0.38/0.17	0.10	0.10
CO (g/km)	1.00	1.14	1.00	1.00
NMHC (g/km)	-	-	-	0.068
PM* (g/km)	-	-	-	0.0045
PN* (#/km)	-	-	-	6*10^11

*Applicable to vehicles equipped with direct-injection engines.

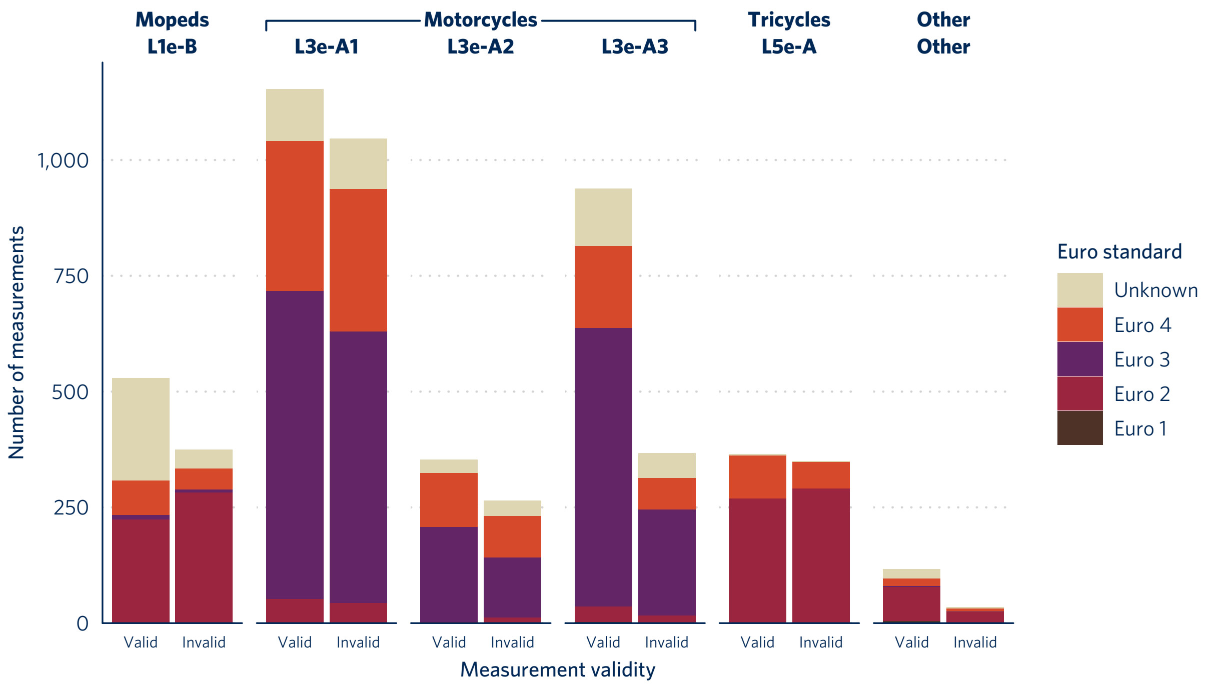


Figure 16. Number of valid and invalid measurements for L-category vehicles by vehicle type, sub-category, and Euro standard. Vehicle types which make up a relatively small percentage of the sampled fleet, like quadricycles and powered bikes, are included in "Other."

Virtually all L-category vehicles in the sample were equipped with petrol engines. The distribution by Euro standard varies by vehicle subcategory. Motorcycles in the Paris sample are predominately Euro 3 and Euro 4, with Euro 3 most common. Mopeds and tricycles are mostly Euro 2 and Euro 4. About 15% of valid measurements could not be assigned to a distinct Euro class.

Figure 17 presents PM, NO_x, and CO emissions results for L-category vehicles by subcategory and Euro standard. Fuel-specific emissions results are shown for NO_x and CO, while PM results are presented in units of nmol/mol. In general, the data show improvement in fuel-specific emissions of CO and NO_x with the implementation of more stringent Euro standards. With the exception of NO_x emissions from medium-sized motorcycles, Euro 4 vehicles had the lowest average emissions for all vehicle subcategories.

Despite this improvement, emissions of L-category vehicles are higher than for petrol passenger cars when expressed on a fuel-specific basis. Average fuel-specific CO and NO_x emissions for L-category vehicles were found to be 2.3–11.1 and 1.2–6.1 times the average emissions for petrol passenger cars, depending on vehicle category. While this gap would be lessened if emissions were compared on a distance-specific basis—L-category vehicles consume less fuel per kilometer than passenger cars—the higher fuel-specific emissions of these vehicles are an indication that real-world emissions reductions for these vehicles have not kept pace with those of other vehicle types.[26] The fuel-specific NO_x and CO emissions of the newest L-category vehicles (Euro 4) observed in the study are more similar to Euro 2 or Euro 3 petrol cars than cars of a similar age (Euro 6).

The PM emissions performance of L-category vehicles varied across vehicle subcategories and Euro standards. This is not surprising, as petrol L-category vehicles were not subject to PM emissions limits up to and through the Euro 4 regulation. PM emissions for L-category vehicles were -0.5–4.4 times those for petrol passenger cars. Euro 5 standards introduce a PM mass limit of 4.5 mg/km, though this applies only to vehicles equipped with direct-injection engines. As noted previously, HC emissions from L-category vehicles are also important to the on-road vehicle emission inventory. Analysis of HC data collected for these vehicles during the Paris study is ongoing and will be reported in a forthcoming publication.

The emissions of L-category vehicles measured in this study are compared against petrol and diesel passenger car emissions in Figure 18. The plots on the left of the figure show a comparison of fleet-average CO, NO_x and PM emissions for each vehicle type, while the plots on the right show results for vehicles certified to current emissions standards only (Euro 6 for passenger cars and Euro 4 for L-category vehicles). Fleet-average CO emissions for L-category vehicles in Paris greatly exceed average emissions from petrol and diesel passenger vehicles. When expressed on a fuel-specific or CO_2-specific basis, average NO_x and PM emissions from L-category vehicles are more similar to diesel than petrol passenger cars. Relative comparisons are similar for the case where only vehicles certified to current standards are considered. Average CO emissions for Euro 4 L-category vehicles in Paris are nearly an order of magnitude greater than emissions from Euro 6 diesel or petrol cars, and fuel-specific NO_x emissions are about 3 times the emissions from Euro 6 petrol cars. PM emissions for Euro 4 L-category vehicles are, on average, almost twice those of Euro 6 cars, though there is a considerable degree of uncertainty in this estimate.

Euro 4 L-category vehicles qualify for the Crit'Air 1 emissions class and so will be allowed to operate without restriction within the Paris LEZ until 2030. Our findings suggest that, on a fuel-specific basis, the CO, NO_x and PM emissions from these vehicles are high relative to other vehicle types that qualify for the Crit'Air 1 emissions classification, like Euro 5 and Euro 6 petrol cars. Without further policy action, L-category vehicles may account for a growing share of on-road emissions within the Paris LEZ as access restrictions are tightened in coming years.

26 Unlike passenger cars, type-approval CO_2 values were not available for the majority of L-category vehicles in the SIV database, preventing the conversion of fuel-specific (g/kg) emission results to distance-specific units (g/km).

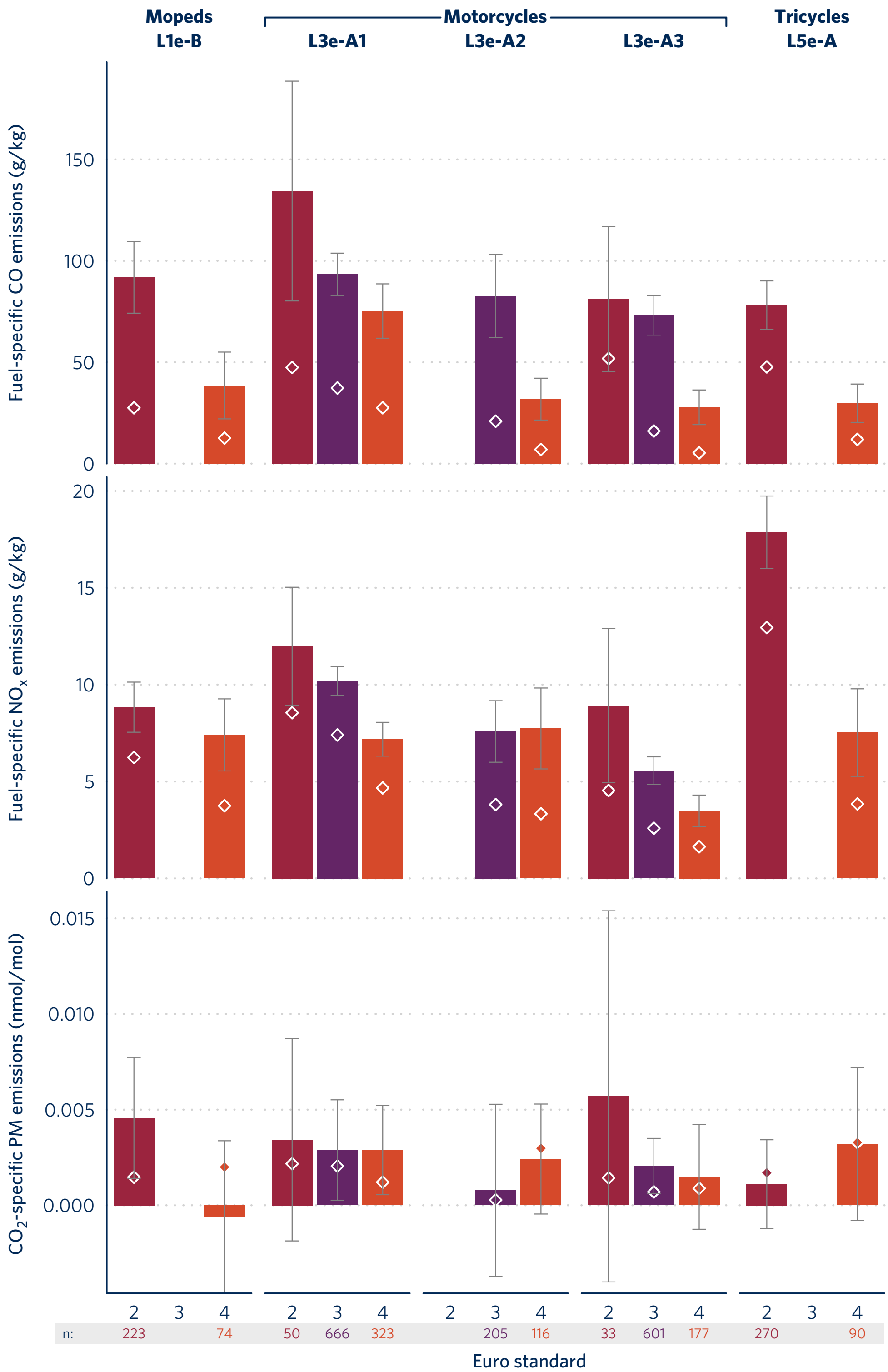


Figure 17. Average CO, NO_x, and PM emissions from L-category vehicles, by vehicle type and subcategory.
Notes: Gray error bars represent 95% confidence interval of the mean and white markers represent the median. The number of measurements is presented below x-axis labels. Data are only plotted for combinations with at least 30 measurements.

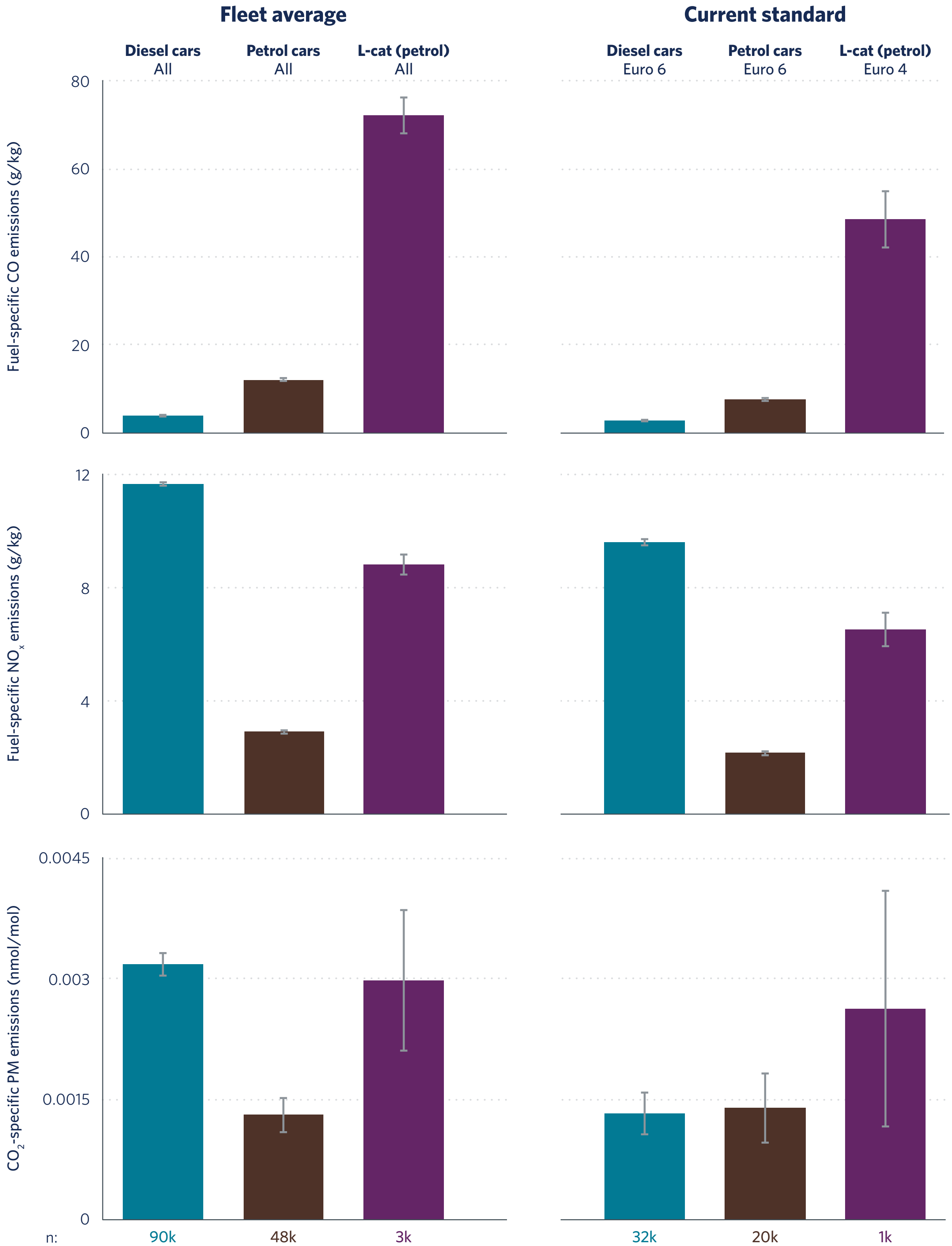


Figure 18. Average CO, NO_x, and PM emissions from L-category vehicles, diesel cars, and petrol cars for the entire measured fleet (left) and for vehicles certified to current Euro standards (right).

BUS EMISSIONS

Buses and coaches operating in Paris are an important source of air pollutant emissions and consequently a key target for air quality improvement initiatives. Régie Autonome des Transports Parisiens (RATP), the main provider of public transit services in the Paris region, has developed an ambitious fleet-renewal plan to guide its transition to a cleaner fleet. The RATP Bus2025 plan calls for the elimination of diesel-powered buses from the fleet by 2025 in favor of zero-emission electric buses and compressed natural gas (CNG) buses fueled with biomethane.[27] Furthermore, Paris, as a signatory of the C40 Fossil Fuel Streets Declaration, has pledged to procure only zero-emission buses from 2025 and to ensure that a large area of the city is zero emission by 2030.[28] Following extensive testing, RATP is now scaling up electric bus procurement. Additionally, diesel-electric hybrid buses have been incorporated into the fleet in high numbers, with 932 of these buses circulating as of September 2018.

These initiatives, in particular the transition to zero-emission electric buses, should significantly improve the environmental performance of buses operating in Paris. However, it will take time to realize these clean bus targets, and in the interim, diesel-powered buses will continue to circulate. About 4,000 measurements of city transit and coach bus emissions were made during the 2018 Paris remote sensing study. These data provide insight into the real-world emissions of buses operating in the city.

Figure 19 presents the total number of measurements and average fuel-specific NO_x emissions for city transit

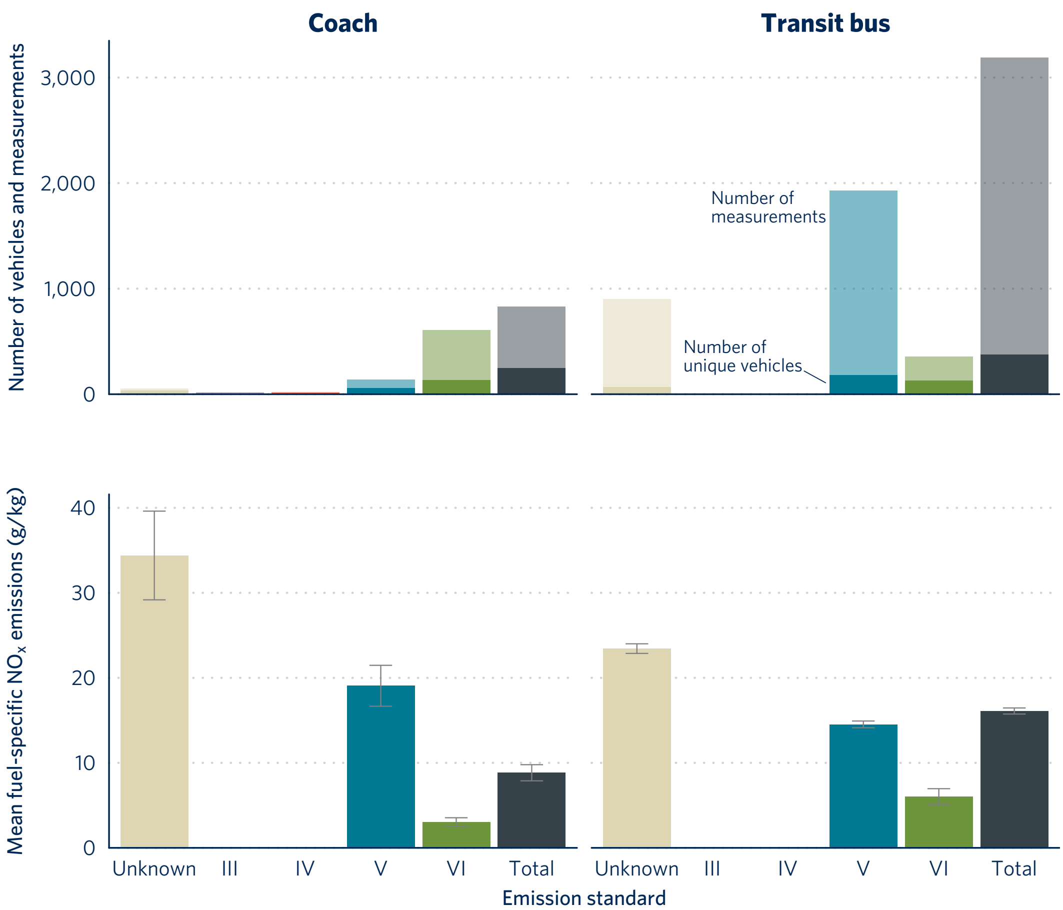


Figure 19. Number of measurements and average fuel-specific diesel NO_x emissions from city transit buses and coaches by Euro standard.

27 RATP, "A 100% environmentally friendly bus fleet thanks to the Bus2025 plan," https://www.ratp.fr/en/groupe-ratp/join-us/a-100-environmentally-friendly-bus-fleet-thanks-bus2025-plan

28 C40 Cities, "Fossil Fuel Free Streets Declaration," https://www.c40.org/other/fossil-fuel-free-streets-declaration

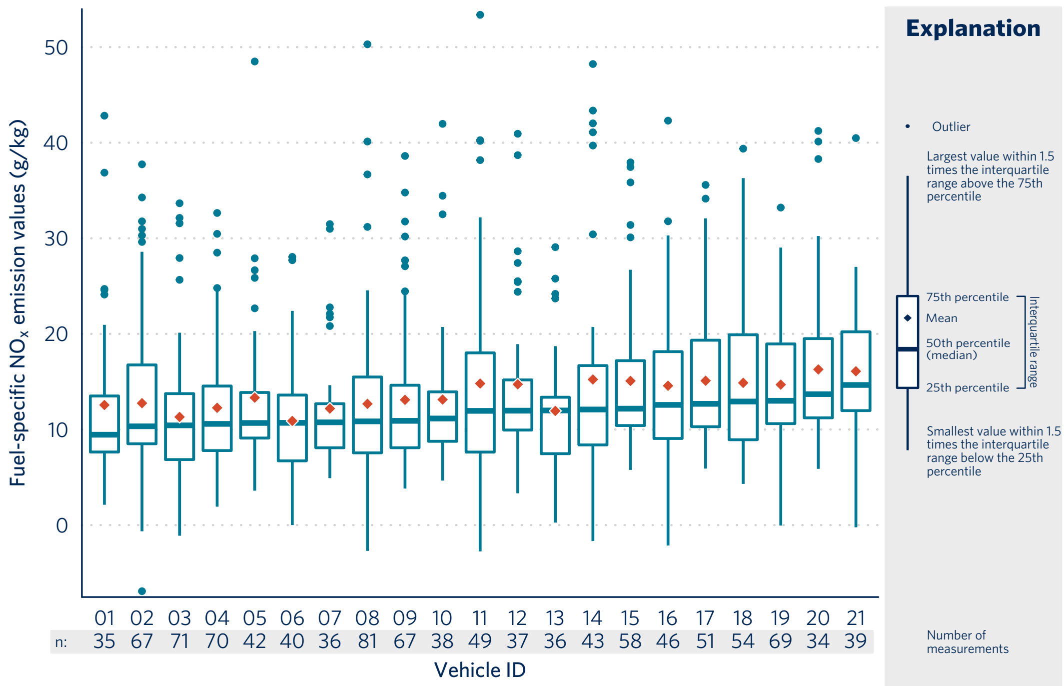


Figure 20. Fuel-specific NO_x emissions for Euro V Scania OmniCity buses.

and coach buses in the Paris dataset. Because sampling was conducted at only three sites during the study, individual buses operating on routes passing these locations were measured many times. While the total sample size for city transit buses was 3,190 records, this represents the emissions measurements of only 378 unique vehicles. Similarly, 249 unique coach buses accounted for a total of 830 emissions records. This means that the results presented here are for a subset of the buses operating in Paris that may not be representative of the broader fleet. However, as will be discussed below, repeated measurements of individual buses presented an opportunity to explore the variability of remote sensing emissions results at the individual vehicle level.

For city transit buses, the greatest number of measurements were for Euro V buses. Coach buses tended to be newer, predominately Euro VI. In both cases, the improvement in NO_x emissions performance of Euro VI buses relative to Euro V buses is readily apparent. On average, fuel-specific NO_x emissions for Euro VI city transit and coach buses were 59% and 84% lower, respectively, than for Euro V buses. These results are consistent with the findings of the TRUE London remote sensing study and provide further evidence of the real-world NO_x emissions benefits of Euro VI buses relative to older diesel technologies.

The Euro standard could not be determined for 28% of city transit bus measurements. The NO_x emissions for the unclassified buses were significantly higher than for Euro V and VI buses, indicating these are likely older vehicles.

During the study, 27 individual city transit buses were measured 30 or more times, representing almost half of the total valid bus measurements. Twenty-one of these buses were Euro V Scania OmniCity buses, and their repeated measurement provides an opportunity to explore the variability in remote sensing emissions test results for individual vehicles. Figure 20 shows fuel-specific NO_x emissions for each of the Scania OmniCity buses measured more than 30 times during the field study. The data are filtered for positive acceleration to remove "non-motoring" events, during which the engine does not power the vehicle (e.g., at idle), and sorted by increasing median NO_x emissions. The NO_x emissions performance of these buses is relatively consistent. The worst-performing bus emitted approximately 1.5 times more NO_x (median) than the best-performing vehicle. All vehicles were observed to experience outlying high-emissions events, with individual NO_x emissions measurements in the range of 30–50 g/kg. These results demonstrate the utility of remote sensing technology in fleet monitoring applications. In this case, sampling individual buses many times allowed for the characterization of both the central tendency (mean, median) of emissions from the buses as well as the intrinsic variability in these emissions.

As was the case in the TRUE London study, the fuel-specific NO_x emissions of Euro VI city transit buses operating in Paris were, on average, lower than the emissions of Euro 6 diesel cars (6.0 g/kg vs. 9.6 g/kg). Ongoing transitions to zero-emission electric buses should deliver significant emissions savings, in particular if these buses replace the oldest diesel buses in the fleet. Further testing is needed to evaluate the real-world emissions performance of CNG buses fueled with biomethane; we did not see any of these buses at the sites used in the study.

EURO 6D-TEMP PASSENGER CAR EMISSIONS

So far, we have grouped all passenger cars certified to Euro 6 standards into a single category when presenting emissions results. The Euro 6 standard, which has been in place since September 2014, has been implemented in a number of phases, with a first series of RDE type-approval limits introduced in the most recent stage, Euro 6d-TEMP. The RDE on-road test requirements are expected to lead to improved real-world emissions performance for Euro 6d-TEMP and 6d vehicles, in particular for NO_x emissions from diesel cars. The Euro 6d-TEMP standards were phased in, starting with passenger cars, beginning in September 2017 and set an on-road not-to-exceed limit for NO_x of 2.1 times the Euro 6 laboratory limit. From January 2020, the Euro 6d (final) standard will lower the NO_x on-road limit to 1.43 times the laboratory limit. The Euro 6d regulation will be fully implemented by 2021 for passenger cars and by 2022 for all light-duty vehicles. As with previous stages of the Euro 6 regulation, under the Euro 6d-TEMP and 6d standards diesel cars are allowed to emit higher levels of NO_x than petrol cars.

To date, limited remote sensing data has been collected for Euro 6d-TEMP cars. Previous measurement studies, like the TRUE London study in winter 2017–2018, occurred before a significant number of these vehicles were on the market, let alone on the road. Figure 21 presents a timeline of the monthly and cumulative

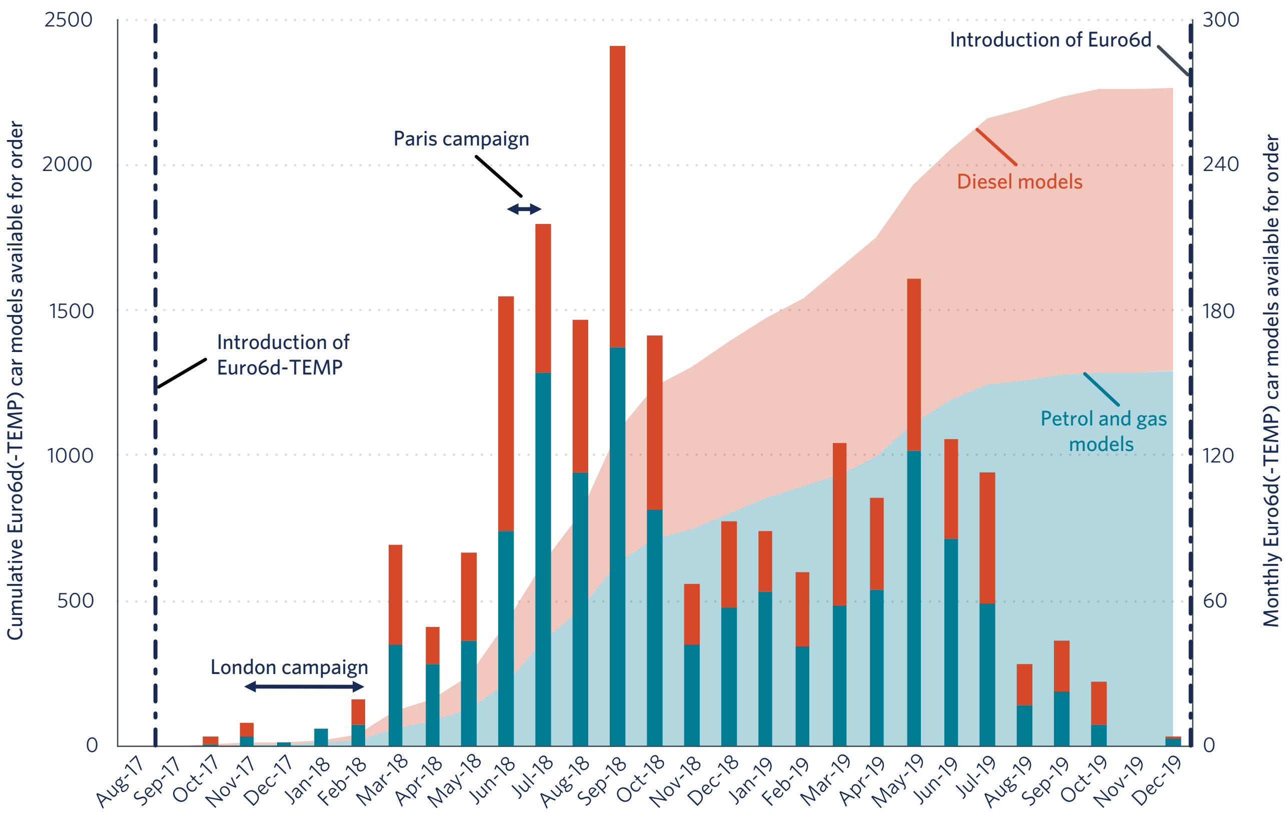


Figure 21. Timeline of the number of Euro 6d-TEMP models available for order (ADAC, 2019; updated June 2019).

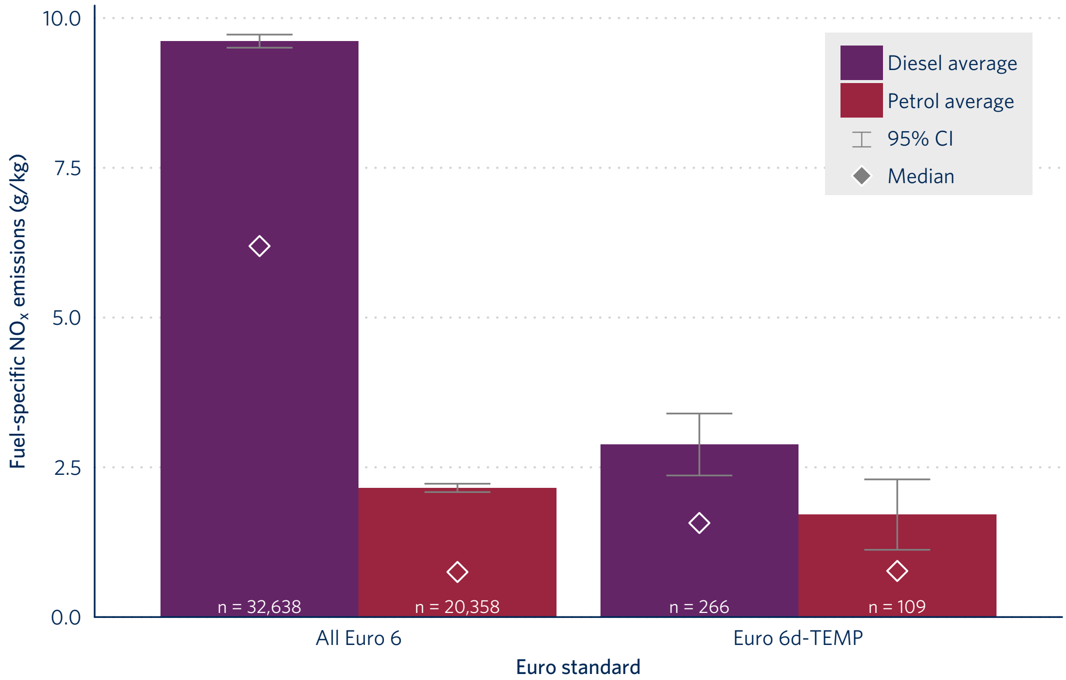


Figure 22. Average fuel-specific NOx emissions by fuel type for all Euro 6 and Euro 6d-TEMP passenger cars in the Paris 2018 dataset.

number of Euro 6d-TEMP models available for order.[29], Euro 6d-TEMP was introduced on 1 September 2017, but very few models were available for order within the first six months. At the time of the Paris campaign, about 550 models were available for order. The peak market entry for diesel and gasoline vehicles occurred two months after the Paris study and one year after the introduction of the new regulation.

In total, the emissions of 375 Euro 6d-TEMP vehicles were measured during the Paris study. Of this sample, 266 vehicles were equipped with diesel engines and 109 with petrol engines. Figure 22 presents fuel-specific NO_x emissions estimates for these vehicles and compares against results for the entire Euro 6 passenger car sample. These results show improvement in the real-world NO_x emissions performance of 6d-TEMP diesel cars. Average fuel-specific NO_x emissions of these vehicles were 2.9 g/kg, 70% lower than those of the remainder of the Euro 6 diesel car sample.

Despite this improvement, the average fuel-specific NO_x emissions for Euro 6d-TEMP diesel cars remain higher than those for petrol cars certified to the same standard.[30] Mean NO_x emissions were slightly lower for Euro 6d-TEMP petrol cars relative to the broader Euro 6 petrol car sample, though these differences could be due to some deterioration of the older Euro 6 vehicles and are likely not statistically significant.

Because there were few Euro 6d-TEMP models on the market at the time of the Paris remote sensing study, the data presented here represents only a small number of Euro 6d-TEMP vehicle families. Five vehicle families accounted for about 80% of all Euro 6d-TEMP vehicle emissions measurements, while the combined Euro 6 data includes 150 vehicle families. Figure 23 presents fuel-specific NO_x emissions data for the Euro 6d-TEMP vehicle families, four diesel and one petrol, and shows the relationship between emissions and VSP. Out of the five vehicle families, four show little dependence of NO_x emissions on VSP. Higher gNO_x/kg of fuel measurements around VSPs of 0 kW/ton are likely due to low CO_2 emissions at these low-load operating conditions, not necessarily due to higher NO_x emissions. One vehicle family, Family D, showed a tendency of increasing NO_x emissions with VSP. The RDE testing protocol defines testing boundaries, including for vehicle dynamics, that lower incentives to reduce emissions to low levels at VSP above 20 kW/t

29 ADAC, „Pkw mit Abgasnorm Euro 6d-Temp, Euro 6d," https://www.adac.de/rund-ums-fahrzeug/auto-kaufen-verkaufen/neuwagenkauf/euro-6d-temp-modelle/. Yoann Bernard, "Real-world NOx emissions from remote sensing: An update of the TRUE rating," https://www.trueinitiative.org/blog/2018/december/real-world-nox-emissions-from-remote-sensing-an-update-of-the-true-rating?author=Yoann+Bernard

30 Mean type-approval CO_2 emissions of petrol and diesel Euro 6d-TEMP were both equal to 112 g/km.

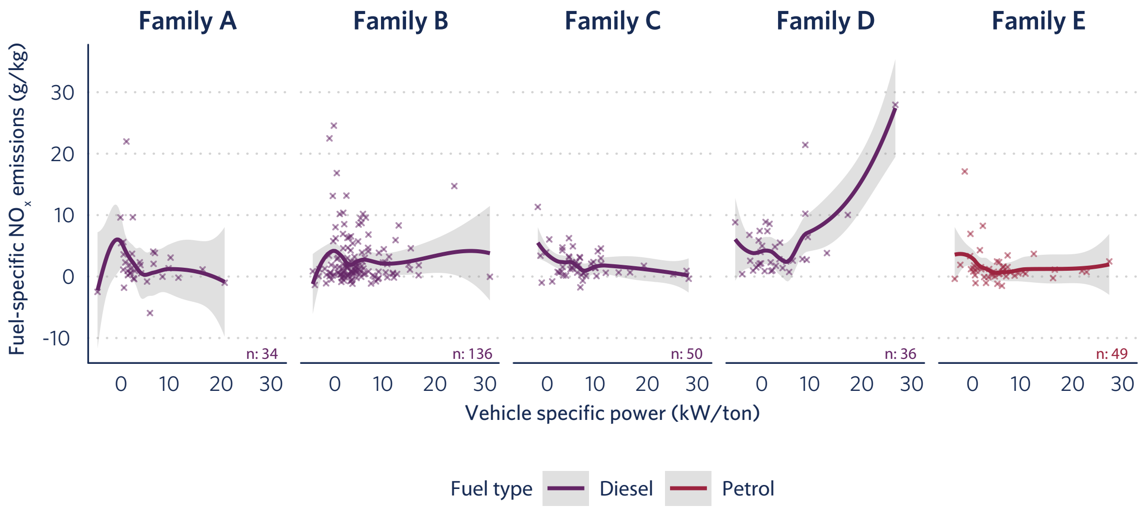


Figure 23. Fuel-specific NOx emissions as a function of VSP for diesel and petrol Euro 6d-TEMP vehicle families with 30 or more measurements. Notes: A locally estimated scatterplot smoothing (LOESS) regression is used to highlight trends.

in urban conditions.[31] It is possible that some Euro 6d-TEMP vehicles will exhibit high NO_x emissions under more dynamic conditions than are encountered on the RDE, similar to what Family D shows in the Paris data. On-road testing of a Euro 6d-TEMP diesel car using a portable emissions measurement system (PEMS) has shown the potential for elevated NO_x emissions at driving conditions outside the scope of RDE-compliant dynamic conditions—in some circumstances up to 18 times the laboratory limit.[32]

While the sample size is small and data are limited to a few groups of manufacturers, the Paris remote sensing data do offer an initial impression of the real-world NO_x emissions performance of Euro 6d-TEMP passenger cars. Additional remote sensing data for Euro 6d-TEMP vehicles, collected over a broader range of driving and ambient conditions, is needed to adequately evaluate the real-world emissions performance of these vehicles. It is important also to bear in mind that all of the Euro 6d-TEMP vehicles measured during the study were less than one year old. The long-term efficiency of diesel aftertreatment systems needed to meet 6d and 6d-TEMP NO_x emissions limits is unknown. Durability requirements have not changed with the introduction of Euro 6d-TEMP standards, and in-service conformity requirements are still limited to five years or 100,000 kilometers, and independent verification of in-use emissions will only be allowed for vehicle models produced from 1 January 2019 onwards. Finally, flexibilities in the current RDE regulation allow 6d-TEMP and 6d vehicles to emit higher levels of NO_x in conditions outside the defined testing conditions. In particular, RDE test protocol boundaries for ambient temperature allow emissions to increase by 60% between 30 and 35 °C, and to be valid an RDE test has to be performed at an ambient temperature that cannot exceed 35°C. Emissions are also allowed to increase at VSP levels above approximately 20 kW/t in urban conditions.

31 Driving on a flat road at 20 km/h, the RDE criteria for 95th percentile is exceeded for acceleration higher than 11 km/h/s. That corresponds to a VSP of about 20 kW/t.

32 Transport & Environment, *Cars with engines: Can they ever be clean?* September, 2018, https://www.transportenvironment.org/sites/te/files/publications/2018_09_TE_Dieselgate_report_final.pdf

RECOMMENDATIONS

Under current policies, all diesel cars, with the exception of plug-in hybrids, will be banned from the Paris LEZ beginning in 2024, when access restrictions will be tightened to allow only zero-emissions vehicles or vehicles with Crit'Air 1 classification into the zone. Today, diesel vehicles do not qualify for Crit'Air 1 classification unless they are plug-in hybrids—i.e., are capable of zero-emission operation. But pressure is growing to relax these requirements and allow Euro 6d-TEMP and newer diesel cars to qualify for the Crit'Air 1 classification.[33]

The results of this study of real-world emissions in Paris do not tend to support such a change. The real-world emissions data for Euro 6d-TEMP vehicles are very limited, and the data that are available indicate that diesel NOx emissions remain much higher than petrol emissions. The long-term performance of Euro 6d-TEMP diesel cars and their emissions under conditions beyond the RDE have yet to be evaluated. Further research is necessary before a picture of the emissions performance of these vehicles can emerge that is sufficiently clear to permit us to conclude that they are comparable to vehicles that currently qualify for Crit'Air 1 classification.

CONCLUSIONS

The TRUE Paris remote sensing study was conducted over 22 days in summer 2018 at three different locations. The emissions of more than 180,000 in-use vehicles were measured, using remote sensing technology. The sampled fleet was mostly made up of passenger cars and light commercial vehicles, but also included considerable numbers of buses, motorcycles, mopeds, and heavy-goods vehicles. The data were collected over a range of ambient temperatures and vehicle operating conditions.

While NO_x emissions from petrol passenger cars in Paris have fallen significantly with the adoption of more stringent emission standards, emissions from diesel cars show little improvement from Euro 2 through Euro 5 emission standards. Euro 6 vehicles show only modest improvement, when emissions are when expressed on a distance-specific basis.

Nitrogen oxide (NO_x) emissions from Euro 6 diesel cars in Paris are 4.8 times the emissions of Euro 6 petrol cars when expressed on a distance-specific basis, and 6 times laboratory limits. On average, NO_x emissions of Euro 6 diesel cars are only 18% lower than those of the oldest, Euro 2, petrol cars observed in the study, and are significantly higher than the emissions of petrol cars certified to Euro 3–Euro 6 standards.

Results from this study build on previous research regarding the influence of driving conditions and ambient temperatures on the NO_x emissions performance of European diesel cars. Variations in engine load and ambient conditions can have a significant effect on NO_x emissions from these vehicles. For diesel cars in Paris, NO_x emissions increased with increasing VSP, consistent with prior findings from European remote sensing studies. Furthermore, NO_x emissions of Euro 5 and Euro 6 diesel cars measured at ambient temperatures above 30 °C were 20% to 30% greater than emissions when temperatures were in the range of 20–30 °C. Compared with Euro 4 diesel cars, Euro 6 emissions were lower in the range of 20–30 °C but were not proportionately lower above 30 °C, suggesting improper calibration above 30 °C.

Emissions of carbon monoxide (CO) from the newest petrol passenger cars and light commercial vehicles in Paris are significantly lower than from older petrol light-duty vehicles in the city's fleet. Emissions of CO from diesel cars are low relative to petrol cars across all Euro standards.

Trends in particulate matter (PM) emissions for passenger cars in Paris are consistent with those observed in other European remote sensing studies. Particulate emissions from petrol cars have historically been low and have shown little change over time. Diesel car PM emissions improved significantly with the use of particulate filters in Euro 5 and Euro 6 cars, to the point where emissions are now in line with those of petrol cars.

This study provides preliminary information on the real-world emissions of L-category vehicles operating in Paris. Analysis of emissions measured from more than 3,400 mopeds, motorcycles, and tricycles shows some improvement in the average fuel-specific CO and NO_x emissions of L-category vehicles with the implementation of more stringent Euro standards.

33 Pierre Zéau, «Les nouveaux diesels seront-ils bientôt éligibles à la vignette Crit-Air 1?» *Le Figaro,* 26 June 2019, http://www.lefigaro.fr/conjoncture/les-nouveaux-diesels-seront-ils-bientot-eligibles-a-la-vignette-crit-air-1-20190626

However, when compared on a fuel-specific basis, the emissions performance of L-category vehicles still lags behind that of other vehicle types, like petrol cars. The fuel-specific CO and NO_x emissions of Euro 4 L-category vehicles are significantly greater than other vehicle groups which qualify for the Crit'Air 1 classification.

The study also produced a substantial real-world emissions dataset for transit and coach buses operating on the three roadways where sampling sites were located. These data, while not representative of the entire Paris bus fleet, allowed for the investigation of NO_x emissions performance by Euro standard and powertrain technology, as well as emissions performance of specific individual buses that were sampled many times during the course of the study. Results further demonstrate the improvement in real-world NO_x emissions of buses certified to Euro VI emission standards relative to older diesel buses. And, echoing similar data collected for London buses in 2017, the fuel-specific NO_x emissions of Euro VI transit buses operating in Paris were, on average, lower than the NO_x emissions of Euro 6 diesel cars.

Average fuel-specific NO_x emissions of Euro 6d-TEMP diesel cars were around 70% lower than those of diesel vehicles certified to earlier stages of the Euro 6 regulation. For three of the four Euro 6d-TEMP diesel vehicle families for which more than 30 measurements were collected, no clear dependence of NO_x emissions on VSP was evident, but the early evidence collected here suggests that NO_x emissions at higher engine loads may be of concern for at least one of the Euro 6d-TEMP diesel vehicle families observed in the study. In any case, average fuel-specific NO_x emissions of Euro 6d-TEMP diesel cars remain higher than Euro 6 petrol cars. And the inconclusive showing regarding influence of VSP on NO_x emissions highlights the need for further real-world emissions testing of Euro 6d-TEMP diesel cars before any well-informed decision could be made regarding whether or not these vehicles should qualify for the Crit'Air 1 classification.

APPENDIX

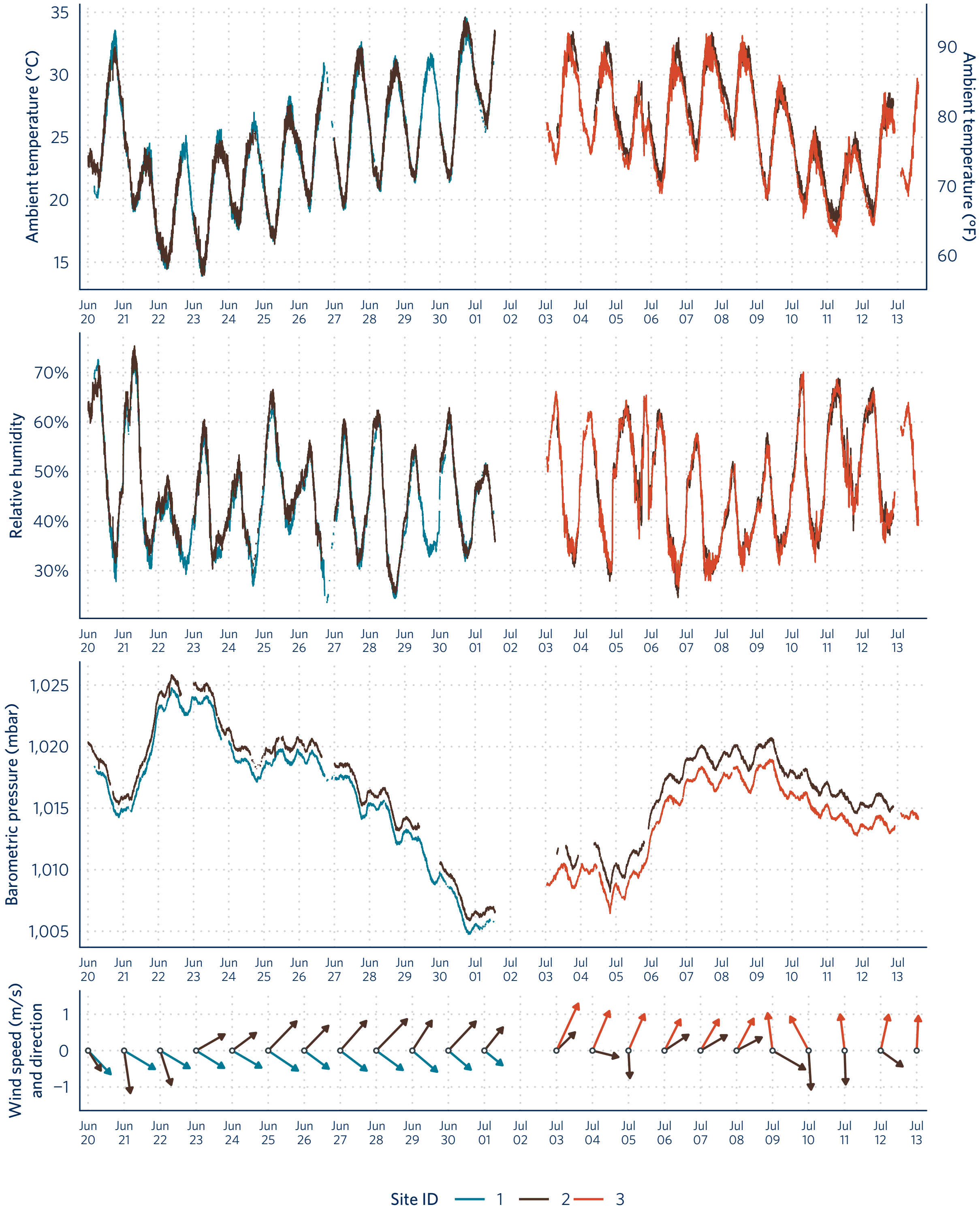


Figure A1. *Ambient conditions recorded at each site. Average daily wind speed is represented by the length of each vector; wind direction is represented by the direction of the vector.*

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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