THE REAL URBAN EMISSIONS INITIATIVE

Evaluation of real-world vehicle emissions in Brussels

Authors: Yoann Bernard, Tim Dallmann, Kaylin Lee, Isabel Rintanen, Uwe Tietge

NOVEMBER 2021

ACKNOWLEDGMENTS

The authors thank GOCA Vlaanderen for their gracious help and for providing the particle number meter; La Sécurité Automobile for their cooperation and critical role in the success of the on-road inspections; Bruxelles Environnement for coordinating project activities; Bruxelles Mobilité for facilitating sampling site access; and SPF Mobilité - La Direction pour l'Immatriculation des Véhicules for providing vehicle characteristics.

This study was funded through the generous support of the FIA Foundation, Bloomberg Philanthropies, and the European Climate Foundation.

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

EXECUTIVE SUMMARY

Motor vehicles are a significant source of air pollutant emissions in Brussels, contributing to the city's air quality challenges and its citizens' negative health outcomes. The Real Urban Emissions (TRUE) Initiative, through its continued efforts to provide cities with detailed information on the real-world emissions of their vehicle fleets, conducted an extensive vehicle emissions testing study in Brussels in Fall 2020. Researchers made more than 260,000 in-use emissions measurements of 130,588 unique vehicles using remote sensing technology. The testing program also included three days of tailpipe particle number (PN) testing to provide a more detailed assessment of particle emissions from light-duty vehicles.

We analyzed data collected during the TRUE Brussels study with the dual goal of identifying the real-world effectiveness of key policies and regulations impacting the Brussels fleet and providing recommendations for their future development. The recommendations we provide address the Low Emission Zone (LEZ) implemented in the Brussels Capital region, the introduction of new stages of European emission standards for new vehicles, and more stringent periodic technical inspection requirements that Belgium has recently introduced.

Several key findings and recommendations follow from our analysis:

- The real-world nitrogen oxide (NO_x) emissions from diesel passenger cars operating in Brussels greatly exceed regulatory limits for vehicle groups not subject to Real Driving Emissions (RDE) type-approval requirements. These groups include vehicles certified to Euro 4, 5, and 6 (pre-RDE) standards, which were found to have real-world NO_x emissions 3, 4, and 5 times the respective laboratory type-approval limits. These results are consistent with TRUE Initiative studies in other European cities.
- The NO_x emissions of Euro 6d-TEMP and 6d diesel cars, which are subject to RDE testing, are 63% and 74% lower than those from vehicles certified to previous stages of the Euro 6 standard. However, average emissions from Euro 6d-TEMP diesel cars remain 60% greater than those of petrol vehicles certified to the same standard.
- Approximately 17% of Euro 6d-TEMP diesel vehicle families exceeded the on-road type-approval not-to-exceed limit, suggesting that the RDE regulation does not sufficiently cover the typical urban driving conditions of Brussels.
- At the time of measurement, RDE-compliant vehicles were relatively young. Due to uncertainty regarding emissions performance as these vehicles and control equipment age, we recommend continued monitoring of the real-world emissions of these vehicles, especially as they will be allowed to operate within the Brussels LEZ until 2030 in the case of diesel vehicles and 2035 for petrol vehicles.
- Euro 4 diesel cars accounted for only 12% of the passenger cars measured during this study. However, we estimated that they contribute 26% of total passenger car NO_x emissions and 47% of total particulate matter (PM) emissions. Similarly, Euro 4 diesel light commercial vehicles (LCV) constituted 15% of the measured fleet but account for more than half of total PM emissions from this vehicle type. These findings indicate new LEZ requirements banning these vehicles starting in 2022 will only impact a small percentage of the fleet but will have a disproportionately positive impact on reducing tailpipe emissions—and PM emissions especially—from light-duty vehicles operating within the city.
- The two light-duty vehicle groups we estimate to account for the greatest shares of NO_x emissions—Euro 5 diesel cars and LCVs—will be allowed to circulate within Brussels until 2025 under the current LEZ implementation schedule. We estimate that these vehicles contribute approximately 40% of total NO_x emissions from passenger cars and nearly 50% of emissions from LCVs. An earlier phase-out would accelerate the NO_x emissions reduction benefits achievable from removing these high-emitting vehicles from the streets of the city.
- Under the proposed timeline for future implementation stages of the Brussels LEZ, pre-RDE Euro 6 diesel cars and LCVs will be allowed to circulate in Brussels only until 2028. The elevated NO_x emissions of pre-RDE Euro 6 light-duty vehicles measured during this study show that this step is warranted. Furthermore, because the real-world NO_x emissions of pre-RDE Euro 6 diesel cars and LCVs significantly exceed those of other passenger vehicle and LCV groups that will be allowed to access the Brussels LEZ from 2025, earlier action could be warranted.

- Approximately 2% of the light-duty diesel vehicles measured in Brussels that were equipped with a diesel particulate filter (DPF) were found to have PM emissions indicative of some level of failure of the emission control system. These findings were consistent with the results of the dedicated tailpipe PN test program, where PN emissions levels for 5% of the tested DPF-equipped diesel fleet well exceeded those expected of vehicles with properly functioning exhaust aftertreatment systems. We estimated this small group of very high-emitting vehicles to be responsible for more than 90% of total particles emitted from the test group. The recent addition of PN testing requirements to the Belgian periodical technical inspection (PTI) program is an important step toward detecting and addressing these high-emitting vehicles. Further benefits could result from tightening high-emitter thresholds and extending requirements to a broader set of vehicles, such as diesel cars and vans certified to Euro 5a standards, petrol vehicles, and other vehicle types like heavy trucks and buses.
- As average PM emissions from diesel and direct injection petrol vehicles are reduced through the application of particulate filters, indirect injection petrol vehicles may serve as an increasingly important source of traffic-related PM emissions in Brussels. We identified one Euro 6 petrol LCV model with real-world PM emissions at a level comparable to those of Euro 4 diesel vehicles, which are not equipped with DPFs. The real-world emissions of indirect injection petrol LCVs warrant further scrutiny.
- Preliminary evidence from this study indicates an increase in diesel ammonia emissions for the latest RDE-compliant vehicles, which now approach the levels of petrol vehicles of the same standard. In both cases, the introduction of tailpipe emission limits in future European emissions regulation would help to limit the impacts of these emissions on urban air quality.
- On average, we found that taxis and ride-hailing vehicles, despite the 7-year vehicle age limit in Brussels, emit about 20% more NO_x per kilogram of fuel burned than passenger cars, which is attributable to higher dieselization rates. However, because most taxis and ride-hailing vehicles are equipped with particulate filters, average PM emissions were, on average, approximately 20% less than those of the relatively older passenger vehicle fleet. Given the high usage rates of these fleets, additional actions to address the elevated real-world NO_x emissions of pre-RDE Euro 6 diesel vehicles should be considered. These actions could include moving Euro 6d LEZ requirements for these vehicles forward, requiring newly registered taxis to be zero emissions capable (as is done in London), and extending these requirements to ride- hailing vehicles.
- Coach buses certified to Euro VI standards emit approximately 60% less NO_x per unit of fuel burned than transit bus equivalents, mainly due to the higher share of Euro VI-D vehicles in the coach bus fleet. Although data on Euro VI-D compliant transit buses was limited, preliminary findings provide evidence in support of requiring all new transit bus fleets to be certified to Euro VI-D standards at a minimum, in order to control the NO_x emissions of the city's bus fleet more effectively. Transitions to zero-emission alternatives would deliver even greater emissions reductions and would help to deliver on the city's long-term ambition to electrify its transit bus fleet.

TABLE OF CONTENTS

LIST OF ACRONYMS

BCR	Brussels-Capital Region
DIV	Direction pour l’Immatriculation des Véhicules
DPF	Diesel particulate filter
LCV	Light commercial vehicle
LEZ	Low emission zone
N_2	Nitrogen
NH_3	Ammonia
NO_x	Nitrogen oxide
NO_2	Nitrogen dioxide
Opus RSE	Opus Remote Sensing Europe
PM	Particulate matter
$PM_{2.5}$	Particulate matter with a diameter of 2.5 micrometers or less
PN	Particle number
PTI	Periodical technical inspection
RDE	Real-driving emissions
RSD	Remote sensing device
STIB	Société des Transports Intercommunaux de Bruxelles
TRUE	The Real Urban Emissions Initiative
VSP	Vehicle specific power

INTRODUCTION

Motor vehicles contribute significantly to poor air quality in the Brussels-Capital Region (BCR) and associated negative health impacts experienced by its citizens. A recent study of the health impacts of air pollution in European cities found that Brussels had the eighth most premature deaths attributable to nitrogen dioxide (NO_2) pollution, of which motor vehicles are a significant source. The report concluded that Brussels could prevent around 530 premature deaths annually if it achieved the ambient NO_2 levels of the least polluted European cities in 2015.[1] Furthermore, motor vehicle emissions contribute to ambient fine particulate matter ($PM_{2.5}$) and ground-level ozone pollution, exposure to which was estimated to be responsible for 627 and 19 premature deaths, respectively, in the BCR in 2018.[2]

The BCR has taken steps to address traffic-related pollution, most notably through the introduction of a Low Emission Zone (LEZ) in 2018. The LEZ, which covers all 19 municipalities in the region, restricts access of high-emitting vehicle groups to the city and currently applies to passenger cars, light commercial vehicles (LCVs), coaches, mini-buses, and buses.[3] Since their introduction, LEZ restrictions have become more stringent. The next implementation step is scheduled for January 2022, when the BCR will extend restrictions to Euro 4 diesel vehicles. The BCR has recently proposed a long-term update to the LEZ schedule, including a further tightening of access requirements and extension to additional vehicle groups, which the region is expected to adopt by the end of 2021.[4] In addition to the LEZ, programs and regulations implemented at the national and European levels also significantly impact the emissions of the Brussels fleet. These regulations include the introduction of new stages of European emission standards for new vehicles and more stringent periodic technical inspection requirements that Belgium recently introduced.

A more detailed understanding of the emissions of vehicles operating on the streets of the city can support the development and implementation of these programs to mitigate the impact of motor vehicles on air quality in Brussels and accelerate transitions to zero-emission transportation. The Real Urban Emissions (TRUE) Initiative works to provide cities with information about the real-world emissions of their vehicle fleets to support evidence-based policymaking. TRUE carried out an extensive emissions testing campaign in Brussels during October and November 2020. During this campaign, researchers made over 260,000 tailpipe emissions measurements of 130,588 unique vehicles using remote sensing technology. Additionally, TRUE collected tailpipe particle number (PN) emissions data for hundreds of vehicles using a tailpipe PN testing instrument recently approved for use in the periodical technical inspection (PTI) programs of three EU member countries.

This report presents the results of the TRUE Brussels real-world emissions testing study. We first provide an overview of the emissions testing campaign and the characteristics of the sampled fleet. We then present emissions results for passenger cars and LCVs, with a focus on implications for the Brussels LEZ, and highlight new data on the real-world emissions of vehicles certified to Euro 6d-TEMP and 6d emission standards. We provide additional context through comparisons with similar datasets collected during previous TRUE studies in other European cities, including London, Paris, and Krakow.[5] Next, we present detailed findings on the real-world emissions of the Brussels taxi, ride-hailing vehicle, and bus fleets. Finally, we report PN emissions testing results and discuss how the findings can be used to assess the prevalence of emission control equipment tampering and malfunctioning in the Brussels fleet.

1 Sasha Khomenko et al., "Premature Mortality Due to Air Pollution in European Cities: A Health Impact Assessment," *The Lancet Planetary Health* 5, no. 3 (March 1, 2021): 121–34, https://doi.org/10/gj2fcr.

2 Karen Van de Vel and Jurgen Buekers, "Interdiction Progressive des Véhicules Thermiques dans la Région de Bruxelles-Capitale : Impact sur la Santé" (VITO NV, February 2021), https://document.environnement.brussels/opac_css/elecfile/RAPP_VITO_Health_Impact_Thermic_Ban_FR.pdf.

3 "In Practice: Everything You Need to Know about the LEZ in the Brussels-Capital Region." Bruxelles Mobilité, accessed October 2, 2021, https://lez.brussels/.

4 A provisional timetable for the phasing out of internal combustion vehicles is available from Bruxelles Environnement at https://environnement.brussels/sites/default/files/user_files/calendrier_de_sortie_du_thermique_2025-2035_1.pdf.

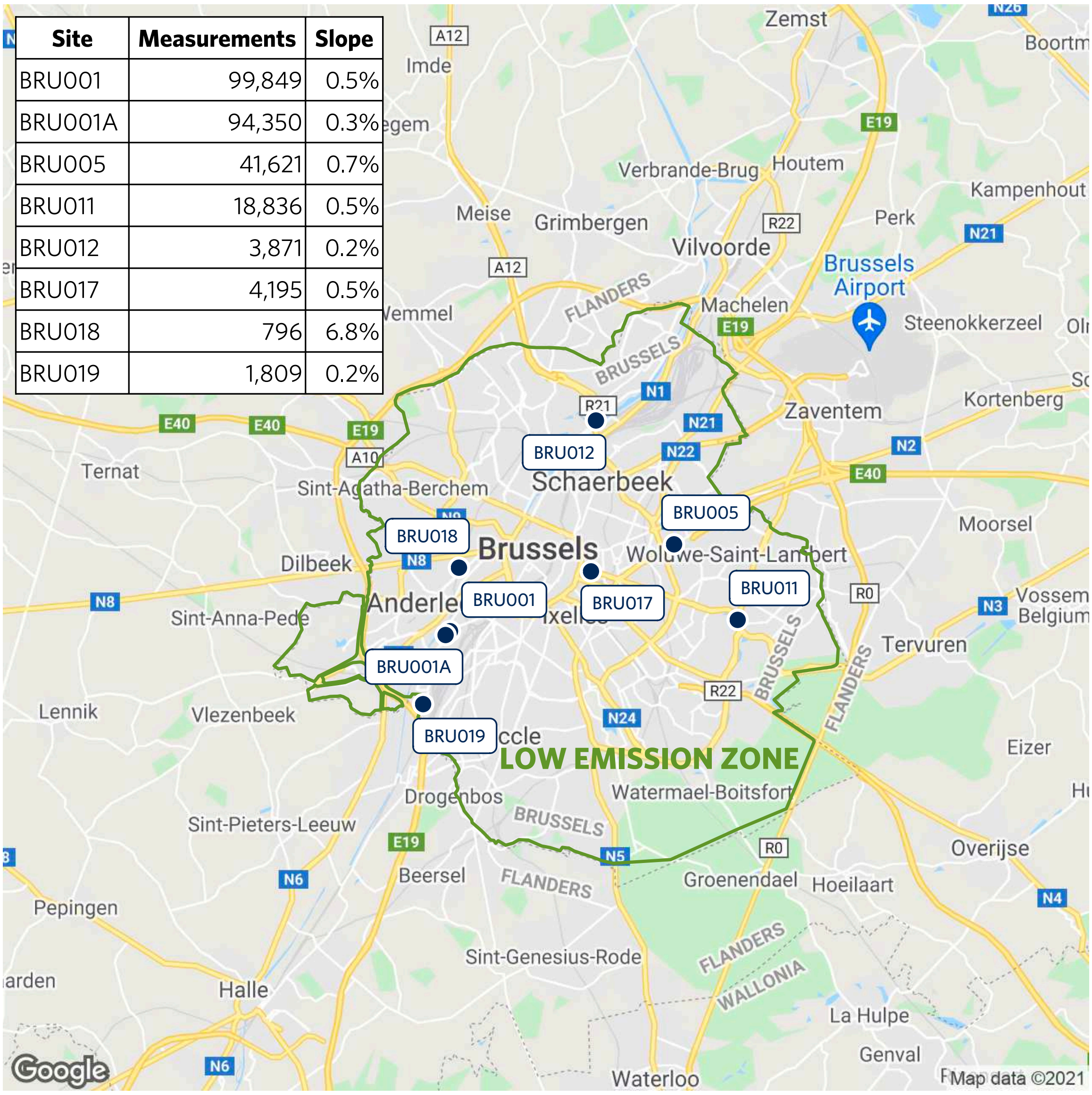
5 See Tim Dallmann et al., *Remote Sensing of Motor Vehicle Emissions in London*, (ICCT: Washington DC, 2018), https://theicct.org/publications/true-london-dec2018 and Tim Dallmann et al., *Remote Sensing of Motor Vehicle Emissions in Paris*, (ICCT: Washington DC, 2019), https://theicct.org/publications/on-road-emissions-paris-201909.

TRUE BRUSSELS REMOTE SENSING STUDY OVERVIEW

DATA COLLECTION

From October through November 2020, the TRUE Initiative conducted a testing campaign for 29 days using remote sensing technology to measure the real-world exhaust emissions from vehicles at eight sites in the Brussels-Capital Region. In total, over 260,000 measurements from 130,588 unique vehicles were collected at eight locations. The sampled fleet included passenger cars, LCVs, taxis, ride-hailing vehicles, and buses. Figure 1 shows the location of the sampling sites, the number of measurements collected, and the road slope at each site. All measurement sites were within the boundary of the Brussels LEZ, which covers the entire territory of the Brussels-Capital Region, including all 19 municipalities.

The emissions testing study was led by Opus Remote Sensing Europe (Opus RSE). Opus RSE deployed two Opus AccuScan™ RSD 5000 units, a type of instrument that TRUE has previously used in remote sensing studies, and two Opus AccuScan™ 5500 units. Although both versions of the instrument measure primary NO_2 emissions, the RSD 5500 includes an



Site	Measurements	Slope
BRU001	99,849	0.5%
BRU001A	94,350	0.3%
BRU005	41,621	0.7%
BRU011	18,836	0.5%
BRU012	3,871	0.2%
BRU017	4,195	0.5%
BRU018	796	6.8%
BRU019	1,809	0.2%

Figure 1. Map of remote sensing measurement sites in Brussels. The inset table shows, for each site, the number of measurements taken in the TRUE study and the road slope.

Figure 2. Remote sensing equipment deployment at the BRU0017 site on Rue de la Loi.

Figure 3. Remote sensing emissions testing of buses at the BRU0018 site on Boulevard Jules Graindor.

enhanced channel for measuring this pollutant. Figure 2 depicts an instance of deployment of the remote sensing equipment during the testing study.

One of the goals of this study was to measure the emissions of buses operating in Brussels. To develop a robust sample for this vehicle type, TRUE deployed remote sensing instruments for four days at a street leading to one of the bus depots used by the Société des Transports Intercommunaux de Bruxelles (STIB), the main public transport operator in Brussels. At this site (BRU0018), two sets of equipment were used: one standard set-up at ground level, and one elevated set of equipment, as shown in Figure 3. The latter was needed to measure emissions from buses with a roof-level exhaust pipe.

As a novel component of the TRUE Brussels campaign, researchers developed and applied new methods to evaluate the performance of diesel particulate filters (DPFs), the key emission control devices used to reduce particulate matter (PM) emissions from diesel vehicles. This approach involved the use of a tailpipe probe to measure the exhaust PN concentrations of individual vehicles. Researchers conducted PN testing over three days, measuring close to 600 vehicles for PM emissions via remote sensing and, on a voluntary basis, for tailpipe PN concentration using the tailpipe particle number instrument (Figure 4). In this report, we analyze the PN results, with a focus on diesel vehicles equipped with DPFs to search for evidence of tampering or malfunctions. We also investigate how the two measurement techniques can be combined

Figure 4. Remote sensing emissions testing and particle number inspections of vehicles at the BRU0019 site on Rue du Lieutenant Lotin.

for an effective screening method to identify high-emitting vehicles.

A description of the data collection campaign, including more detailed information on sampling locations, instrumentation, and measurement approach, can be found in a fieldwork and methodology report prepared by Opus RSE.[6]

DATA PREPARATION AND ANALYSIS METHODS

The methods used to prepare and analyze remote sensing data collected during the TRUE Brussels study follow those developed and applied in previous studies led by the ICCT and TRUE.[7] We converted tailpipe pollutant concentration ratios to distance-specific estimates in grams per kilometer (g/km), the unit used in European light-duty vehicle regulations, by combining the average pollutant emissions from the remote sensing records with vehicle type-approval CO_2 emission and real-world fuel consumption values.[8] The engine load is estimated using vehicle specific power (VSP), or the instantaneous power to mass demand, in kilowatts per ton (kW/ton), that is determined by speed, acceleration, road grade, and generic values of the aerodynamic and rolling resistance of vehicles.

Remote sensing measurements are most useful when basic technical characteristics such as fuel type, emissions standard, make, model, and age of the sampled vehicles can be retrieved from vehicle registries via the license plate number. In the Brussels data, we sourced the vehicle information from La Direction pour l'Immatriculation des Véhicules (DIV), the federal vehicle registration authority. In Belgium, license plate information is specific to the owner rather than the vehicle. Consequently, the vehicle information in the DIV linked to a specific plate number may have changed if the owner replaced the vehicle during this campaign. Therefore, we merged two sets of vehicle specifications sourced from the DIV: one from the beginning of the campaign (September 2020), and the other from the end of the campaign (December 2020). The vehicle specifications were the same between the two datasets for the vast majority of license plates (98.2%). For approximately 1.7% of plates, owners had changed their vehicles. These plates were excluded from this analysis, as we could not link vehicle information to the measurements with certainty. For less than 0.1% of plates, the vehicles were the same but with some updates to specifications. In these cases, we considered DIV information from December 2020 as the most up-to-date dataset.

The Opus instrument distinguishes valid from invalid emissions measurements based on the series of absorption records along each exhaust plume. The default emissions validity criteria are tailored for high- and low-emitter screening programs that grade vehicle emissions performance based on a single measurement. The instrument judges a measurement as valid only if it has captured enough of the vehicle exhaust plume. That strategy aims to increase the confidence for that single emissions record, while discarding records that might lead to false positives. In an earlier study, Opus RSE had provided a second series of validity criteria tailored for emissions monitoring of a wider fleet, tolerating smaller exhaust plumes. We used these criteria for this study.

In the results presented below, we compare the Brussels measurements with a reference dataset. That reference dataset, referred to as the TRUE sample, is based on earlier TRUE studies from London, Paris, and Krakow. We selected these datasets because they each had a similar scope, contained over 100,000 measurements collected in a major European city, and occurred relatively recently, within the past four years. Note that, throughout the report, we use blue graph elements for Brussels and brown elements for the TRUE dataset comparison. All whiskers and shaded areas in graphs refer to 95% confidence intervals of the mean.

SAMPLE OVERVIEW

During this campaign, we measured the emissions of 265,327 vehicles using remote sensing instruments. Out of this sample, 237,681 records met the criteria established to determine a valid emissions

6 OPUS RS Europe, "TRUE –The Real Urban Emissions Initiative, Brussels 2020, Fieldwork and methodology report," (2021). https://theicct.org/sites/default/files/OpusRSE-ICCT_Fieldwork_Brussels_25-08-2021_clean.pdf

7 Yoann Bernard et al., *Determination of Real-World Emissions from Passenger Vehicles Using Remote Sensing Data*, (TRUE Initiative: Washington DC, 2018), https://theicct.org/publications/real-world-emissions-using-remote-sensing-data; Uwe Tietge et al., *A Comparison of Light-Duty Vehicle NO_x Emissions Measured by Remote Sensing in Zurich and Europe* (Canton of Zurich Office for Waste, Water, Energy and Air, 2019), https://theicct.org/publications/LDV-comparison-NOx-emissions-Zurich.

8 Vehicles CO_2 type-approval information is assumed to be based on the new Worldwide Harmonized Light Vehicle Test Procedure (WLTP) for Euro 6d-TEMP vehicles, and on the New European Driving Cycle (NEDC) for other Euro standards. The gap between type-approval and real-world CO_2 is addressed in Jan Dornoff, Uwe Tietge, and Peter Mock, *On the Way to "Real-World" CO_2 Values: The European Passenger Car Market in Its First Year after Introducing the WLTP*, (ICCT: Washington DC, 2020), https://theicct.org/publications/way-real-world-co2-values-european-passenger-car-market-its-first-year-after.

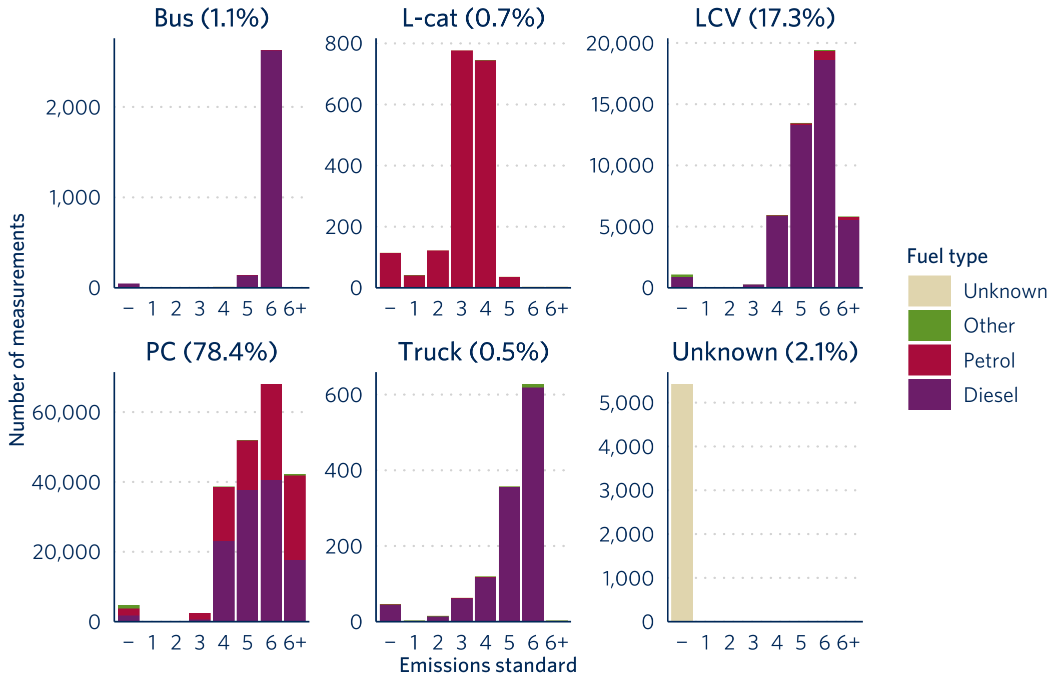


Figure 5. Number of remote sensing measurements by vehicle class, estimated emissions standard, and fuel type. 6+ refers to the Euro 6d-TEMP and 6d emission standards. Dashes (–) represent vehicles for which the Euro standard could not be determined.

measurement. We were able to retrieve vehicle technical specifications for 232,743 of the valid emissions records.

Figure 5 presents an overview of the Brussels sample by vehicle category, fuel type, and emissions standard. It reflects all data records, including invalid emission measurements and measurements for which we could not retrieve vehicle specifications, to show a complete picture of the vehicle fleet in Brussels at the time of the campaign.

Passenger cars make up the majority of the sample (78%), with LCVs (17%), buses (1%), L-category vehicles (motorcycles, mopeds) (0.7%), and trucks (0.5%) accounting for most of the remaining identifiable vehicles. The vehicle category could not be identified for 2% of measurements.

Data on fuel type shows diesel vehicles were most prevalent in the sample, accounting for 64% of total measurements. Petrol vehicles accounted for nearly all of the remaining measurements. For the two most common vehicle types observed in the study (passenger cars and LCVs), diesels accounted for 58% and 97%, respectively, of the total sample.

In Figure 5, we group vehicles certified to Euro 6d-TEMP and 6d standards as Euro 6+. These vehicles accounted for 20% of passenger cars and 13% of LCVs observed in the study. These vehicles are type-approved under the Real Driving Emissions (RDE) regime, which was introduced from September 2017 for passenger cars and for LCVs under a reference mass of 1,305 kg, and from September 2018 for heavier categories of LCVs.

Euro 5 and Euro 6 (Euro 6+ excluded) are the most common Euro standards for light-duty vehicles. For passenger cars, these standards represented 25% and 33% of the total passenger vehicle sample, respectively. For LCVs, Euro 5 and Euro 6 accounted for 29% and 42% of the total LCV sample, respectively. Petrol vehicles constituted the vast majority of pre-Euro 4 passenger cars, in line with the LEZ requirements that have restricted access to pre-Euro 4 diesels since 2020. Access restrictions for petrol vehicles applied only to pre-Euro 2 vehicles at the time of the campaign. During the whole campaign, only 309 unique light-duty vehicles out of 104,933 (less than 3%) did not comply with LEZ requirements. Nearly all of these vehicles were diesels. These results indicate an overall high compliance level with the LEZ access limitations.

Figure 6 shows the share of vehicle types observed at each of the eight sampling sites. The vehicle distribution at seven of the eight sampling sites was similar, with passenger vehicles and LCVs making up 79% and 18% of the fleet, on average. The exception was the BRU018

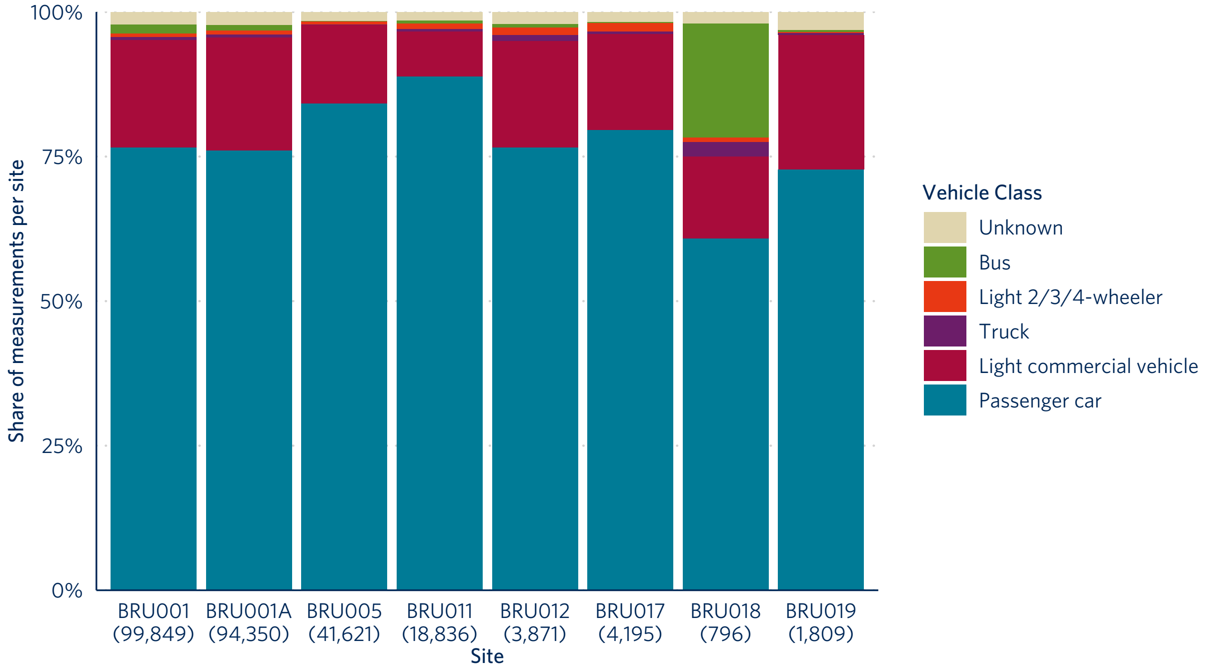


Figure 6. Share of vehicle categories by measurement site. Numbers in parentheses denote the number of measurements taken in the TRUE study.

site, located next to the bus depot and where a high-exhaust RSD captured emissions from certain buses. Here, buses made up 20% of the fleet, and the site was responsible for 6% of the total bus measurements we made during the study.

Table 1 summarizes testing conditions and passenger car fleet characteristics in the Brussels measurements for records with vehicle specification information. We compare Brussels data with average results from remote sensing measurements made in other TRUE remote sensing emissions testing campaigns carried out in Krakow (2019), London (2017–2018), and Paris (2018). The table groups the data by fuel type and emissions standard to facilitate comparison within and across subsamples of the data.

Vehicles measured in Brussels were, on average, 6 years old, which is 1 year younger than the average age of vehicles in the TRUE database at the time of measurement. For earlier emission standards, Brussels vehicles are older on average, as the measurements included in the TRUE reference dataset were made from 2017 through 2019. This effect is more pronounced for early emission standards, for which vehicles in Brussels were up to 3 years older than in the reference dataset.

The mean NEDC type-approval CO_2 emissions level was 126 g/km in Brussels and 133 g/km in the reference dataset. We conducted measurements in Brussels in the Fall, with median ambient temperatures around 19 °C–20 °C—about 3 degrees colder than the reference dataset. The mean vehicle-specific power (VSP), an estimate of the power demand during the measurement relative to the mass of the vehicle, was 8.2 kW/ton, compared to 5.5 kW/ton for the TRUE data, indicating moderately higher engine loads, on average, for the vehicle fleet measured in Brussels. The average speed in the Brussels data was 34 km/h (3 km/h higher than TRUE) and the average acceleration was 2.0 km/h/s (1.3 km/h/s higher than TRUE).

The Brussels remote sensing campaign stands out from other TRUE studies in several ways. First, on average the Brussels fleet is younger than the fleet from former TRUE campaigns. In addition, the Brussels fleet has an exceptionally low share of pre-Euro 4 diesel vehicles, attributable to the LEZ access restrictions in place for this vehicle group. The dieselization rate of passenger cars in Brussels was relatively high at 58.2%—much higher than in the Krakow and London campaigns at 39.6% and 43.7%, respectively, but still lower than in Paris campaign with 63.0%. Finally, the Brussels remote sensing dataset significantly expands the coverage of Euro 6d-TEMP and 6d passenger cars, which respectively make up 17% and 3.2% of passenger vehicle measurements. The increased prevalence of these vehicles relative to past TRUE studies allows for a more detailed assessment of their real-world emissions performance than was previously available.

Table 1. Summary of remote sensing testing conditions and passenger car fleet characteristics in Brussels (blue) and the reference database (brown).

Fuel	Measurements	Avg. vehicle age (years)	Avg. road grade	Certified CO_2 emissions (g/km, NEDC)	Avg. ambient temperature (°C)	Avg. vehicle-specific power (kW/ton)	Avg. speed (km/h)	Avg. acceleration (km/h/s)
Euro 3 Diesel	573 15,002	16 15	0.5% 1.8%	162 140	19.8 25.5	9.4 5.4	34 31	2.3 0.8
Euro 3 Petrol	1,854 21,215	17 15	0.5% 1.7%	180 153	19.9 21.7	8.5 5.7	34 34	2 0.7
Euro 4 Diesel	23,055 35,905	13 10	0.5% 1.7%	146 146	19.8 23.2	8.8 5.3	34 31	2.1 0.7
Euro 4 Petrol	15,457 36,032	14 11	0.5% 1.6%	152 149	19.6 20.8	8.3 5.5	34 33	2 0.7
Euro 5 Diesel	37,605 57,123	8 5	0.5% 1.7%	125 126	19.5 21.8	8.7 5.4	34 31	2.1 0.7
Euro 5 Petrol	14,218 36,995	8 6	0.5% 1.7%	128 127	19.0 21	8 5.5	34 32	1.9 0.7
Euro 6 Diesel	40,437 52,874	3 2	0.5% 1.7%	116 116	19.0 22.7	8.5 5.6	34 30	2 0.8
Euro 6 Petrol	27,391 46,514	3 2	0.5% 1.8%	119 117	18.8 23.3	8.2 5.6	34 32	1.9 0.8
Euro 6d-TEMP Diesel	14,954 1,037	1 0	0.5% 1.7%	119 117	19.0 28.8	8.6 6	34 33	2 0.9
Euro 6d-TEMP Petrol	20,109 2,498	1 1	0.5% 1.7%	124 119	18.9 29.7	8.4 6.3	34 36	2 0.9
Euro 6d Diesel	2,703 0	0 -	0.5% -	109 -	19.2 -	9.1 -	34 -	2.2 -
Euro 6d Petrol	4,036 0	0 -	0.5% -	100 -	19.0 -	8.8 -	34 -	2.1 -
Total	202,392 305,195	6 7	0.5% 1.7%	126 127	19.2 22.4	8.5 5.5	34 32	2 0.8

Note. NEDC = the New European Driving Cycle.

ANALYSIS AND RESULTS

The following sections present the findings of our analysis of vehicle emissions data collected during the TRUE Brussels remote sensing campaign. We start with results for passenger vehicles and LCVs, the two most prevalent vehicle groups in the Brussels fleet. We then turn to findings for specific fleets, including taxis, ride-hailing vehicles, and buses. Finally, we present the results of the three-day campaign to measure tailpipe PN concentrations.

PASSENGER CAR NITROGEN OXIDES EMISSIONS

Figure 7 shows the average fuel-specific NO_x emissions of passenger cars in grams of NO_x emitted per kilogram of fuel burned (g/kg) by fuel type and emissions standard and compares the levels found in the Brussels and TRUE data. The average NO_x emissions of petrol vehicles decreases consistent with the introduction of more stringent Euro standards. This finding follows a trend observed in previous TRUE studies. In contrast, prior to the introduction of Euro 6 standards, we

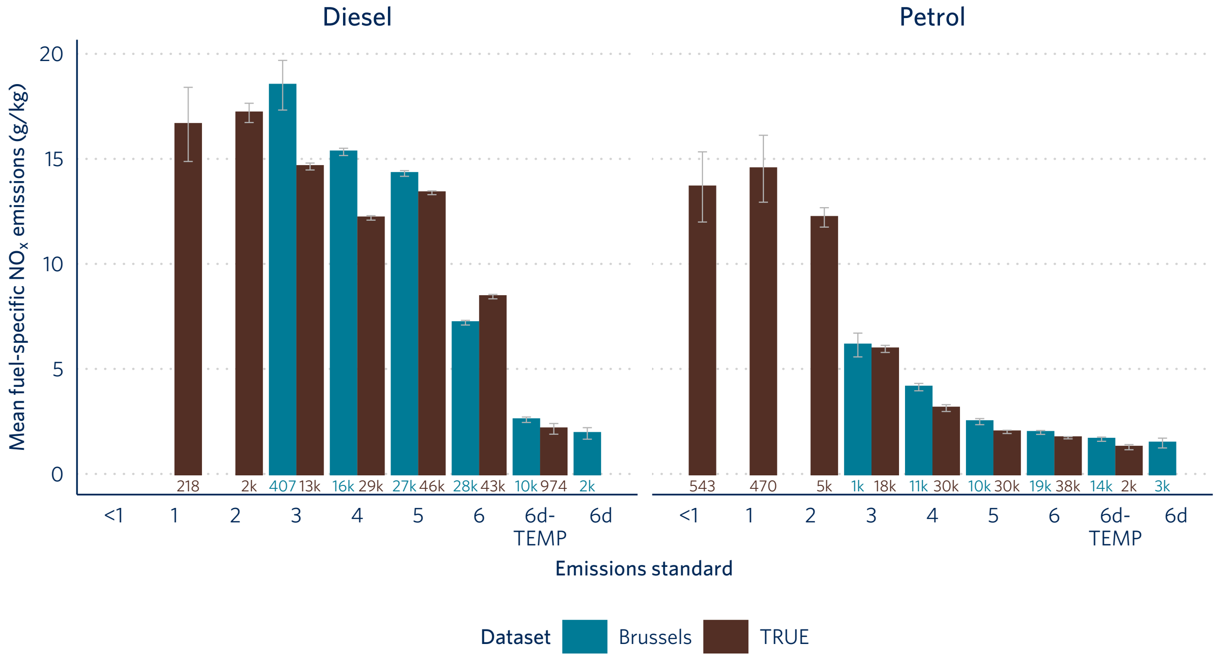


Figure 7. Mean fuel-specific NO_x emissions from diesel and petrol passenger cars by emissions standard for Brussels and TRUE remote sensing data. The number of measurements is presented below each bar. Whiskers represent the 95% confidence interval of the mean. Only results for groups with at least 100 measurements are shown.

observe little improvement in the NO_x emissions of diesel cars. When implemented in September 2014, the Euro 6 standard lowered the NO_x emissions limit for diesel cars by 67%. Later implementation stages of the Euro 6 standard, starting with the 6d-TEMP step, introduced RDE on-road type-approval testing requirements. The results of the Brussels testing indicate that the latest Euro standard implementation steps have resulted in significantly lower real-world NO_x emissions for diesel cars, especially those meeting RDE testing requirements. Relative to pre-RDE Euro 6 diesel vehicles, the average fuel-specific NO_x emissions for Euro 6d-TEMP and 6d-certified diesel cars were 64% and 73% lower, respectively. While the emissions gap between diesel and petrol cars certified to the latest standards has dropped relative to previous Euro standards, average real-world NO_x emissions for Euro 6d-TEMP and 6d diesel cars remain around 50% higher than petrol cars certified to the same standards.

Except for Euro 6 diesel cars, the average fuel-specific NO_x emissions measured in Brussels for each passenger car group surpassed the average values measured in previous TRUE studies. The most likely explanation for the higher emissions we observed in Brussels is that vehicles belonging to a common Euro standard were 1-3 years older at the time of testing compared to the average of the previous studies, with emissions deterioration through aging leading to higher emission rates.[9] We investigated whether operating conditions as measured by vehicle VSP could explain the observed differences in NO_x emissions and found that these discrepancies are largely independent of VSP (see Figure A1 in the appendix). The effects of ambient temperature, a known factor of influence for diesel car emissions, also could not explain the differences.

Pre-RDE Euro 6 diesel vehicles were the only passenger car group measured in Brussels for which average NO_x emissions stood noticeably lower than the average emissions measured in previous TRUE studies. To investigate this finding, we compare in Figure 8 the fuel-specific NO_x emissions of diesel passenger cars by registration year for the various Euro 6 implementation steps. We differentiate between ambient temperature ranges within the TRUE data, where brown lines represent the full temperature range and red lines represent data between 15 °C–22 °C, corresponding to the 25th and 75th percentile of temperatures we encountered during the Brussels campaign.

9 Jens Borken-Kleefeld and Yuche Chen, "New Emission Deterioration Rates for Gasoline Cars – Results from Long-Term Measurements," *Atmospheric Environment* 101 (January 2015): 58–64, https://doi.org/10.1016/j.atmosenv.2014.11.013; Yuche Chen and Jens Borken-Kleefeld, "NO_x Emissions from Diesel Passenger Cars Worsen with Age," *Environmental Science & Technology* 50, no. 7 (April 5, 2016): 3327–32, https://doi.org/10.1021/acs.est.5b04704.

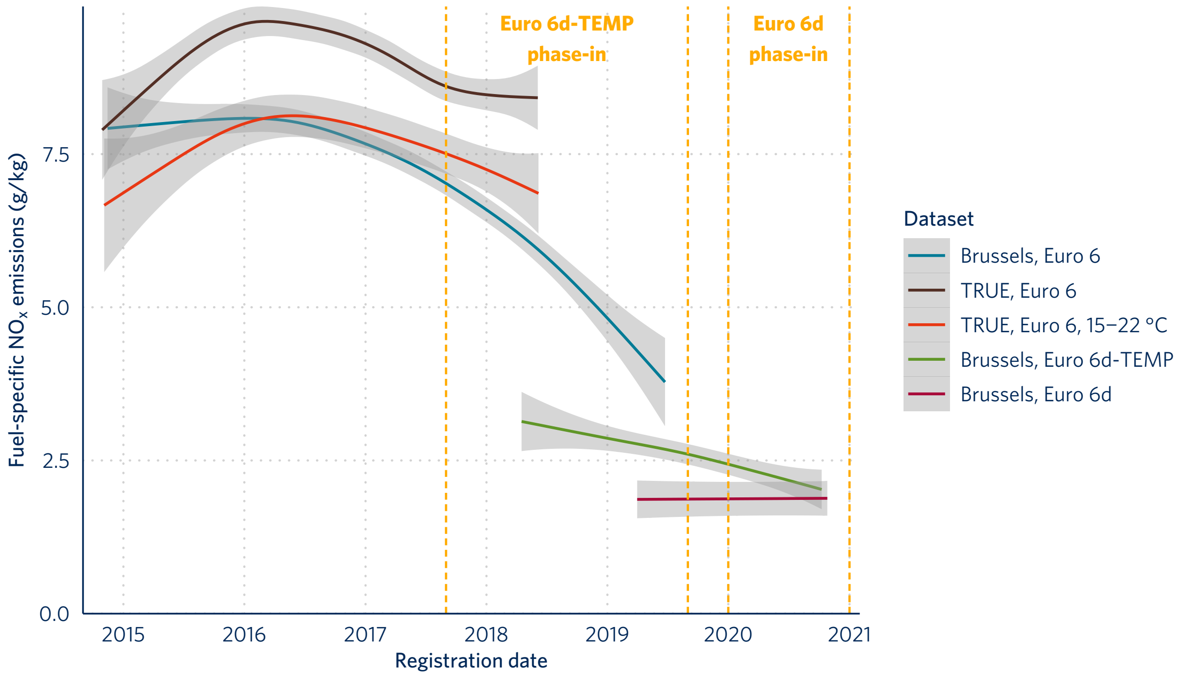


Figure 8. Fuel-specific NO_x emissions from Euro 6 diesel passenger cars by registration date.

The average NO_x emissions of Euro 6 passenger cars measured in Brussels are comparable to results from previous TRUE campaigns for similar ambient temperatures and for vehicles with similar registration dates. In both cases, NO_x emission levels for pre-RDE vehicles peak for vehicles registered around early 2016 and then decline. The observed decline in NO_x emissions after 2016 is likely attributable to manufacturer responses to increased scrutiny of real-world emissions from diesel cars following the emergence of the Dieselgate scandal in 2015. By 2017, manufacturers such as Fiat-Chrysler and Renault-Nissan had announced software updates to their upcoming engine calibration strategies and a voluntary service action for cars already on the road to improve their NO_x emissions on a wider range of driving conditions.[10] The greater prevalence of newer, lower-emitting Euro 6 certified vehicles in the Brussels fleet likely explains some of the differences in the observed NO_x emission factor for this group compared with the TRUE reference dataset.

After the European Union (EU) introduced RDE testing requirements in the Euro 6d-TEMP standard implemented between September 2017 and 2019, manufacturers progressively began adopting more robust emission control systems to meet the requirements. Figure 8 illustrates the clear improvement in real-world NO_x emissions from RDE type-approved vehicles, certified to Euro 6d-TEMP and 6d standards. From 2018, our data shows some overlap in which registered vehicles were certified to different Euro 6 implementation steps in a given year. This overlap occurred because manufacturers were allowed some flexibility with end-of-series derogations that enabled them to put a limited number of vehicles on the market after the introduction of 6d-TEMP and 6d standards. Also, the vehicle database could be incomplete; some of the Euro 6 vehicles in the Brussels dataset could actually be RDE type-approved.

Using the methods described above, we converted fuel-specific NO_x emission factors to g/km units to better compare real-world data with regulatory emission limits. Figure 9 presents the average distance-specific NO_x emissions by fuel type and emissions standard separately for the Brussels and TRUE datasets. The overall trend for distance-specific emission rates mirrors the trend observed for fuel-specific emissions shown in Figure 7. Consistent with past TRUE studies in European cities, the Brussels data indicate that the real-world NO_x emissions of diesel passenger cars exceed regulatory limits at each Euro standard. For the most common diesel vehicle groups—Euro 4, 5, and 6—real-world NO_x emissions were 3, 4, and over 5

10 Yoann Bernard, "Fiat-Chrysler, Renault-Nissan . . . Who Might Be Next?" *ICCT Staff Blog*, January 30, 2017, https://theicct.org/blogs/staff/fiat-chrysler-renault-nissan-who-might-be-next.

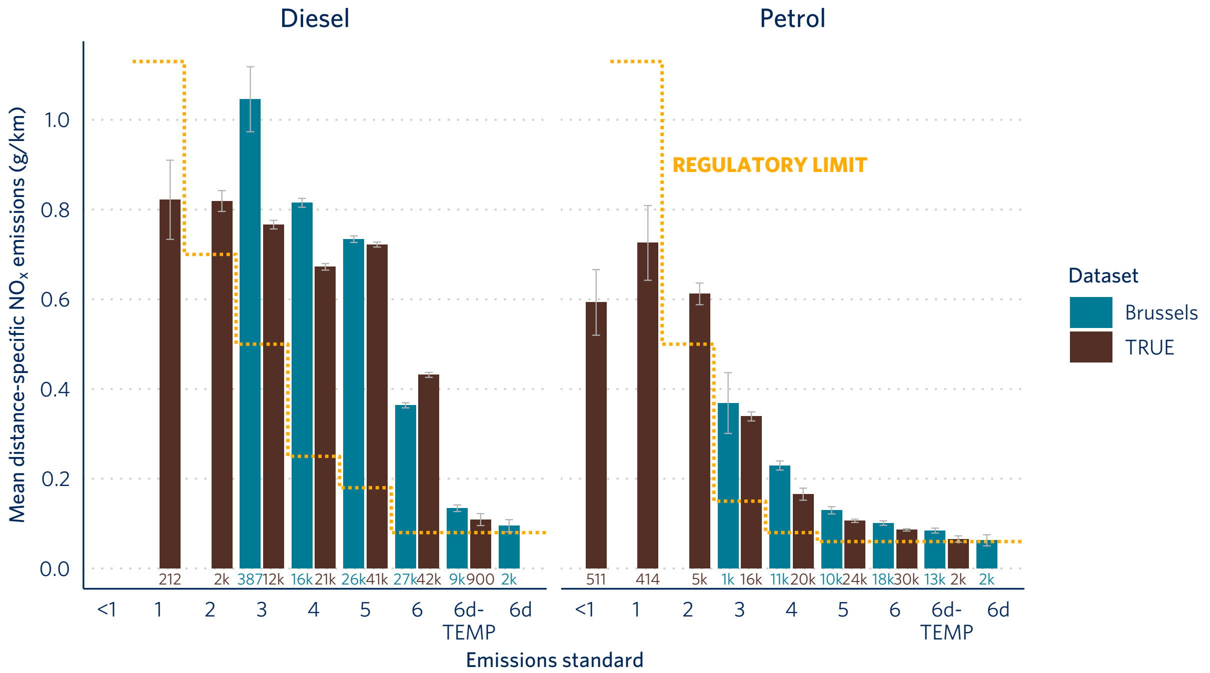


Figure 9. Mean estimated distance-specific NO_x emissions from diesel and petrol passenger cars by emissions standard for Brussels and TRUE remote sensing data. The number of measurements is presented below each bar. Whiskers represent the 95% confidence interval of the mean. Only results for groups with at least 100 measurements are shown.

times the corresponding limit value. Similarly, with the exception of the Euro 6d group, the real-world emissions of petrol cars exceeded regulatory limits, though to a lesser extent than did diesel cars. For Euro 6d-TEMP vehicles, the average NO_x emission factor for diesel cars, 0.134 g/km, was 60% greater than the emission factor for petrol cars (0.084 g/km). Euro 6d-certified cars show continued improvement relative to the Euro 6d-TEMP implementation step, with average real-world NO_x emission factors for these vehicles approaching regulatory limits.

A unique aspect of the TRUE Brussels dataset is that the larger sample size of Euro 6d-TEMP vehicles allows for a more detailed analysis of the emissions from this group than previous studies made possible. Figure 10 plots the average distance-specific NO_x emissions of Euro 6d-TEMP passenger cars by fuel type and vehicle make for the Brussels remote sensing dataset. Average distance-specific NO_x emissions by make ranged from 0.057 g/km to 0.220 g/km for diesel cars and from 0.021 g/km to 0.123 g/km for petrol cars.

Figure 10 also shows the respective laboratory and on-road emission limits for each fuel type. During their type-approval process, 6d-TEMP vehicles are allowed to emit up to 2.1 times the laboratory limit when tested under RDE test conditions. This permission translates to an on-road limit of 0.168 g/km for diesel cars and 0.126 g/km for petrol cars. The average real-world NO_x emissions for most vehicle makes are less than on-road, real-driving emission limits. However, the data show that the average NO_x emissions for five diesel vehicle makes exceeded the on-road limit. Note that these results do not necessarily indicate that these vehicles are not compliant. Rather, the data may indicate that these vehicles perform worse in actual urban conditions than during their on-road type-approval testing. One possible reason for the discrepancy is that the urban portion of an RDE test used for type-approval is much longer than a typical city trip, and high emissions after cold start tend to be more prevalent in a typical urban journey.[11] Approximately one third of makes met the laboratory type-approval limit of 0.06 g/km for petrol, whereas only 12.5% met the laboratory type-approval limit of 0.08 g/km for diesel vehicles. As some makes have small sample sizes and very wide ranges in 95% confidence intervals, however, more data collection is needed to understand fully the real-word emissions from these vehicle makes.

11 Felipe Rodríguez et al., *Recommendations for Post-Euro 6 Standards for Light-Duty Vehicles in the European Union* (ICCT: Washington DC, 2019), https://theicct.org/publications/recommendations-post-euro-6-eu.

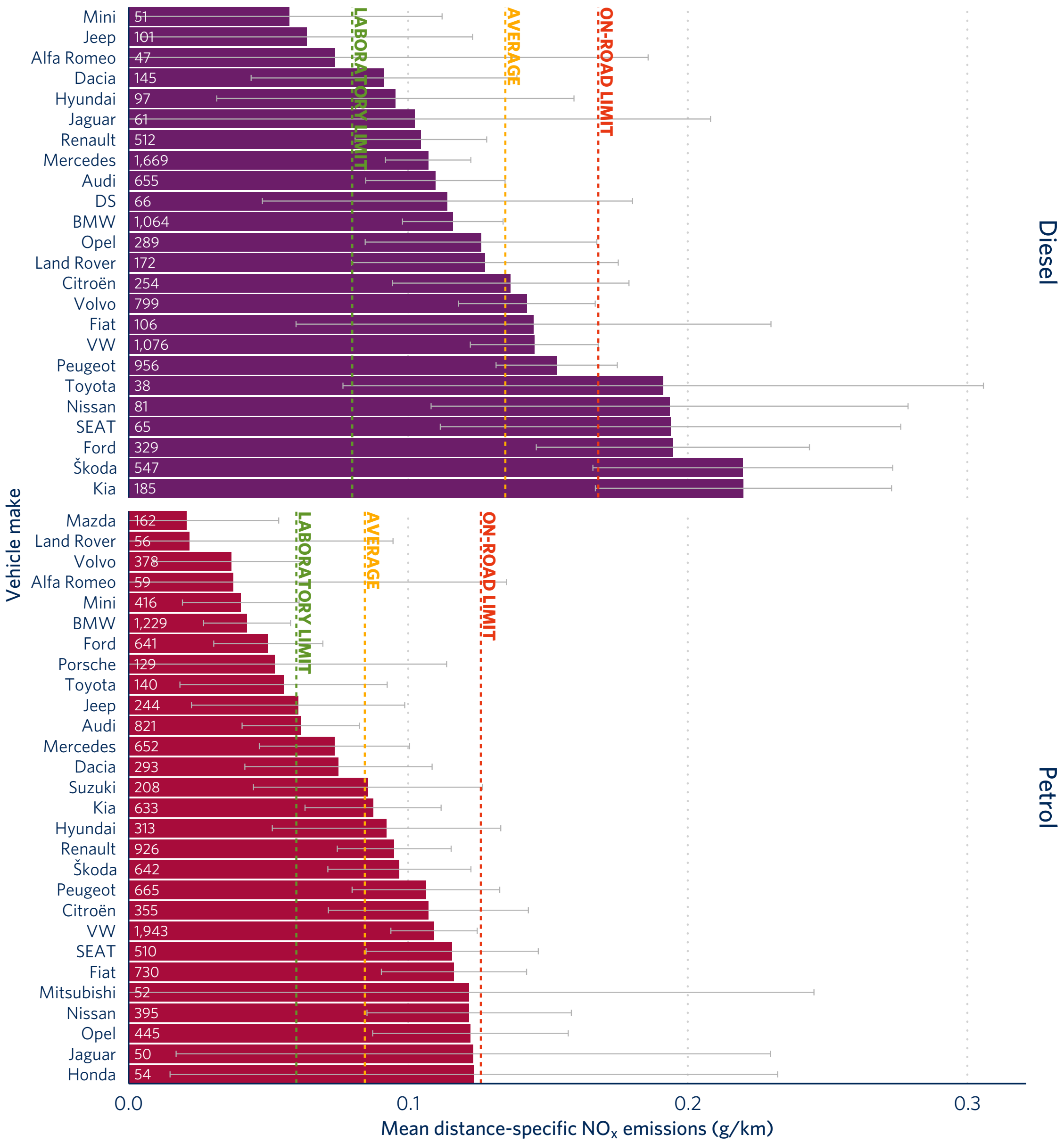


Figure 10. Mean distance-specific NO_x emissions from Euro 6d-TEMP passenger cars by fuel type and make for Brussels remote sensing data. The number of measurements is presented on each bar. Whiskers represent the 95% confidence interval of the mean. Only results for groups with at least 30 measurements are shown.

By combining the Brussels data for 6d-TEMP vehicles with similar data collected in previous TRUE studies, we are able to develop a sufficient sample to characterize NO_x emissions for individual vehicle families, defined as unique combinations of fuel type, Euro standard, manufacturer group, and engine displacement. Figure 11 presents the mean distance-specific NO_x emission for Euro 6d-TEMP passenger car families, calculated using the combined dataset. We include a full listing of emission results by vehicle family in the Appendix (Table A1). Approximately 31% of petrol vehicle families met the laboratory type-approval limit of 0.06 g/km, whereas only 8% of diesel vehicle families met the laboratory type-approval limit of 0.08 g/km. In addition, 17% of vehicle families exceeded the on-road type-approval limit of 0.168 g/km for diesel vehicles, and 8% exceeded the on-road type-approval limit of 0.126 g/km for petrol vehicles.

The foregoing results have focused on the real-world emission factors for specific vehicle groups. By combining these estimates with information about the share of these vehicle groups in the Brussels fleet, we estimate the relative contributions of each group

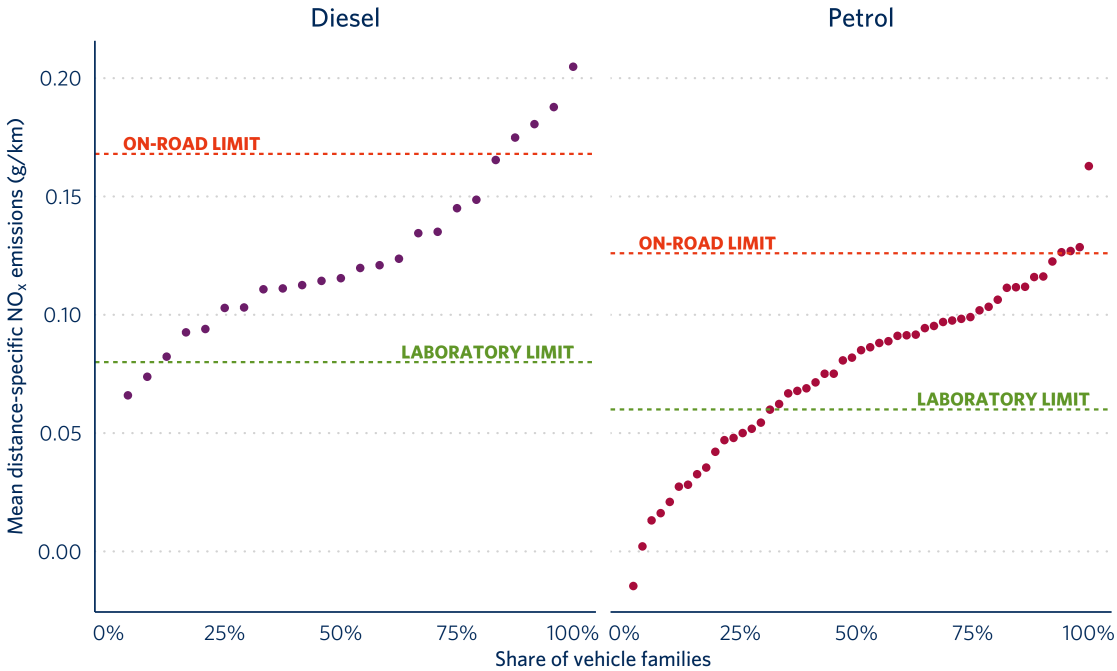


Figure 11. Mean distance-specific NO_x emissions from Euro 6d-TEMP passenger cars, by vehicle family, for Brussels and TRUE remote sensing data combined.

to total NO_x emissions in the city. These calculations are useful for evaluating the impacts of policies that target specific vehicle groups, such as the Brussels LEZ. Figure 12 plots the estimated share of NO_x emissions from passenger cars and the share of measurements by fuel type and emissions standard. In this case, we use the share of measurements as a proxy for the activity share of each vehicle group in the fleet distribution. The results indicate that diesel cars certified to Euro 4, 5, and 6 standards contribute the highest shares of total passenger car NO_x emissions. We estimate that together, these groups are responsible for approximately 80% of the NO_x that the Brussels passenger car fleet emits. Euro 5 diesel cars contributed the highest share of NO_x emissions— nearly 40%—while only accounting for 20% of total measurements. Similarly, Euro 4 diesel cars were responsible for a disproportionate amount of NO_x emissions relative to their presence in the fleet; we estimated this group to account for 26% of NO_x emissions, while making up only 12% of measurements.

The findings presented in Figure 12 have important implications for the further development of the Brussels LEZ. From 2022 onwards, Brussels will tighten access restrictions to the LEZ area to exclude Euro 4 diesel passenger vehicles. The results of the TRUE Brussels study show that this vehicle group accounts for 26% of passenger car NO_x emissions, suggesting that the next stage of the Brussels LEZ will significantly reduce NO_x emissions within the city. However, the 2022 implementation stage will continue to allow access to the highest emitting vehicle group—Euro 5 diesel cars. The current implementation timeline for the Brussels LEZ will ban diesel Euro 5 cars beginning in 2025. Our results suggest that an earlier phase-out of diesel Euro 5 cars could accelerate NO_x emissions reductions. For comparison, the London Ultra Low Emission Zone has restricted pre-Euro 6 diesel cars since April 2019, and Paris plans to ban diesel completely by 2024 across the entire city.

Brussels is expected to adopt the schedule for future implementation stages of the LEZ by the end of 2021. Under the current proposal, pre-RDE Euro 6 diesel cars will be allowed to circulate in Brussels until 2028, when restrictions will tighten to allow access only to vehicles meeting Euro 6d emission standards at a minimum. Results from the TRUE Brussels testing program show that NO_x emissions from pre-RDE Euro 6 diesel cars exceed laboratory test limits by 5 times and exceed RDE-compliant diesel car emissions by 3 to 4 times when expressed on a per kilometer basis. Figure 12 shows that this vehicle group accounted for the largest share of measurements and is responsible for about 20% of total passenger car NO_x emissions. Both fleet and emissions shares for this group may

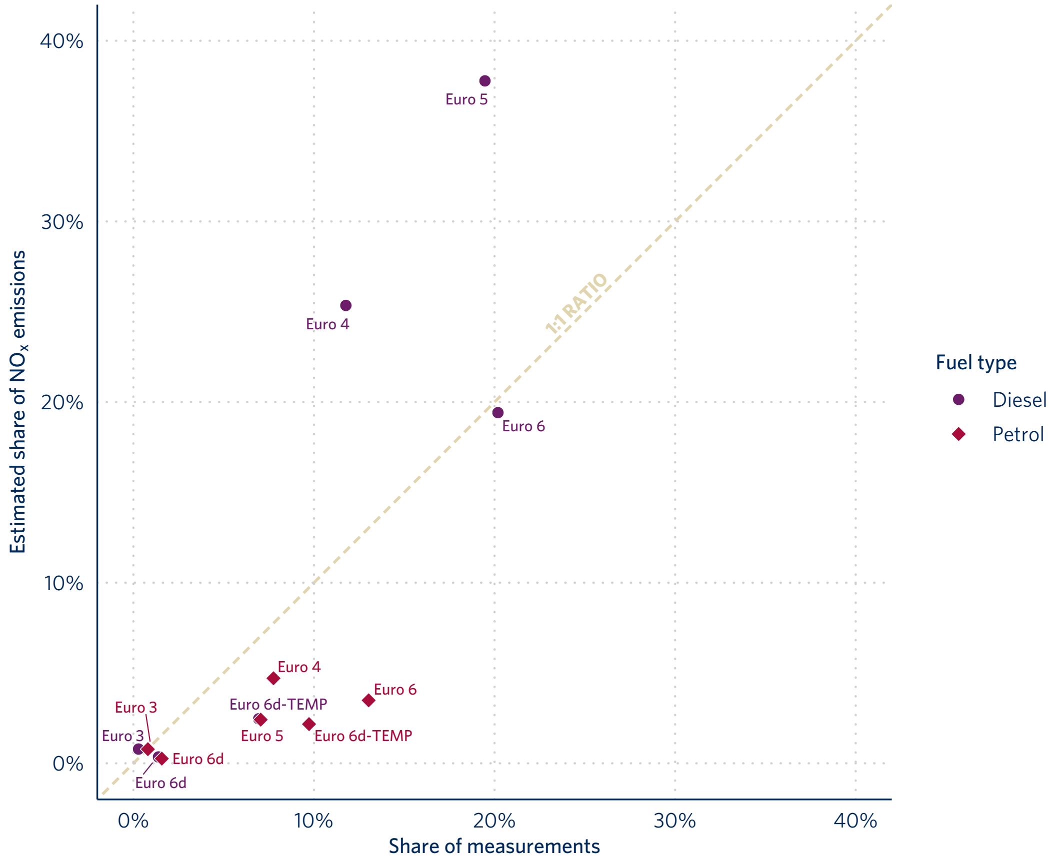


Figure 12. Share of measurements and estimated share of total NO_x emissions from passenger cars in Brussels by emissions standard and fuel type. The share of remote sensing measurements is used as a proxy for vehicle-kilometers travelled by each group of vehicles.

increase as Euro 4 and 5 diesel cars are banned in coming years. Based on these findings, the Brussels LEZ implementation step banning these vehicles is warranted. Because the real-world NO_x emissions of pre-RDE Euro 6 diesel cars significantly exceed those of other passenger vehicle groups that will be allowed to access the Brussels LEZ from 2025, earlier action could be considered for these vehicles, such as banning pre-RDE Euro 6 diesel cars in 2025 rather than 2028.

PASSENGER CAR PARTICULATE MATTER EMISSIONS

Particulate emissions from mobile sources directly impact human health and are linked to premature death and disease in urban populations. We analyzed the remote sensing opacity measurement as a proxy for the mass of exhaust PM.

Figure 13 presents average fuel-specific PM emissions from passenger vehicles. Note that PM measurements from the 2018 Paris campaign are not included in the TRUE average, as the Paris measurements were collected using the Hager Environmental & Atmospheric Technologies (HEAT) Emissions Detection and Reporting (EDAR) instrument and are not directly comparable with Opus RSD measurements.

As shown, the PM emission trends by Euro standard that we observed in Brussels are consistent with those measured in other European cities. Petrol passenger cars measured in Brussels show a relatively low level of fuel-specific PM emissions across all emission standards. For diesel passenger cars, the introduction of more stringent PM mass emission limits and PN limits in the Euro 5 standard effectively forced the use of DPFs in engine designs. The impacts of the widespread use of this emission abatement technology are clearly visible in the Brussels data, where average PM emission factors are estimated to have fallen by over 80% from diesel Euro 4 to Euro 5. Fuel-specific PM emissions of diesel vehicles certified to Euro 6 and later standards are comparable to those of petrol cars of the same standards. Despite the improvement in average

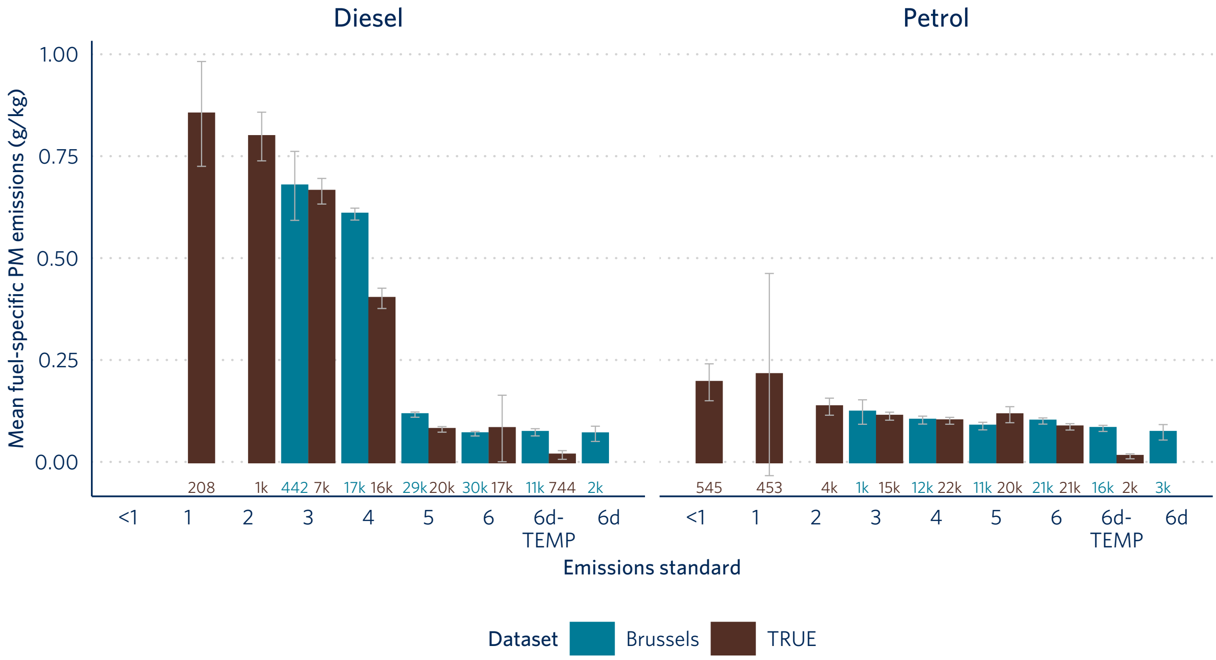


Figure 13. Mean fuel-specific PM emissions from diesel and petrol passenger cars by emissions standard for Brussels and TRUE remote sensing data. The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean. Only results for groups with at least 100 measurements are shown.

PM emissions from diesel cars with the widespread application of DPFs, we observe individual Euro 5 and 6 vehicles with high fuel-specific PM emissions and discuss these findings further below.

Figure 14 plots the estimated share of PM emissions from passenger vehicles and the share of measurements by fuel type and emissions standard. Overall, we estimate diesel cars to be responsible for 75% of total PM emissions. Most of these emissions come from Euro 4 diesel cars, which account for 47% of total emissions while only constituting an estimated 12% of the passenger car fleet. These results suggest the next phase of the Brussels LEZ, which extends access restrictions to Euro 4 diesel vehicles beginning in 2022, will significantly reduce the total tailpipe PM emissions from passenger cars operating in the city.

PASSENGER CAR AMMONIA EMISSIONS

Ammonia (NH_3) emissions from motor vehicles are of concern for urban air quality, as they contribute to the formation of secondary PM in the atmosphere. Though NH_3 emissions from light-duty vehicles are not yet regulated in Europe, current discussions surrounding the next stage of European emission standards, Euro 7, indicate new limits may be set for NH_3 emissions.[12] Understanding the extent of real-world NH_3 emissions will be important in order to define the scope of the issue and identify which vehicle groups have the highest emissions. Recent studies of NH_3 emissions from motor vehicles have found that current emission inventories underestimate transport contributions to total emissions[13] and that transport can surpass the agriculture sector as the primary source of NH_3 emissions in European cities.[14]

The remote sensing instrument used for the Brussels campaign was equipped with a prototype channel for measuring NH_3 emissions. Although researchers calibrated this channel before the campaign, the channels did not receive daily calibration and checks as is done with other pollutant channels to ensure measurement accuracy and consistency. For this reason, we do not present the NH_3 data here with the same

12 CLOVE Consortium, "Additional Technical Issues for Euro 7 LDV" (Advisory Group on Vehicle Emission Standards, Brussels, April 27, 2021), https://circabc.europa.eu/w/browse/f57c2059-ef63-4baf-b793-015e46f70421.

13 Naomi Farren et al., "Underestimated Ammonia Emissions from Road Vehicles," *Environmental Science & Technology* 54 (December 22, 2020): 15689–97, https://doi.org/10.1021/acs.est.0c05839.

14 Miriam Elser et al., "High Contributions of Vehicular Emissions to Ammonia in Three European Cities Derived from Mobile Measurements," *Atmospheric Environment* 175 (February 1, 2018): 210–20, https://doi.org/10.1016/j.atmosenv.2017.11.030.

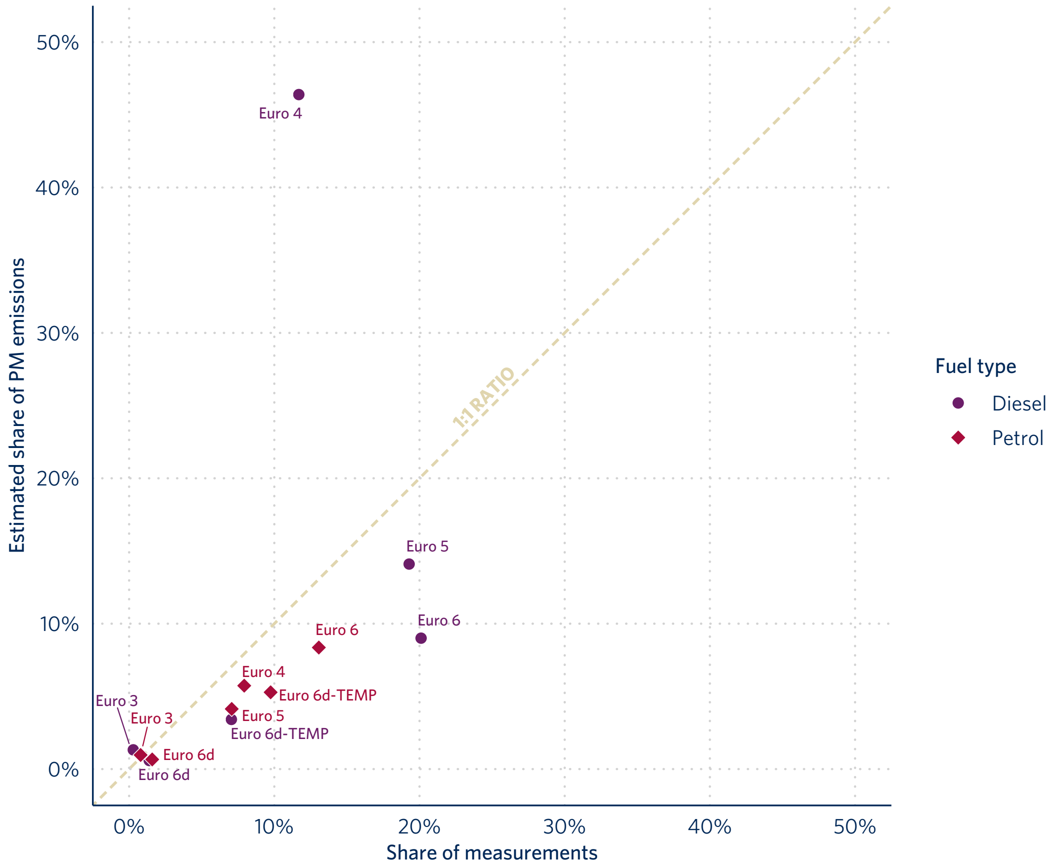


Figure 14. Share of measurements and estimated share of total PM emissions from passenger cars in Brussels by emissions standard and fuel type. The share of remote sensing measurements is used as a proxy for vehicle-kilometers travelled by each group.

level of confidence as we do for other pollutant data in the study because the measurement results may have suffered from a shift over time and may have been left uncorrected during the course of the project. Despite these limitations, we believe the data can still be useful for investigating the relative emissions performance of vehicle groups and present findings on NH_3 emissions.

Figure 15 presents average fuel-specific NH_3 emissions from passenger vehicles. The results are consistent with previous studies of NH_3 emissions from light-duty vehicles and show NH_3 emission rates for petrol vehicles tend to be higher than those for diesel cars. NH_3 emitted by petrol vehicles is a by-product of the three-way catalyst used to control NO_x, carbon monoxide, and hydrocarbon emissions. Our findings show NH_3 emissions from petrol passenger cars decrease with each new Euro standard. This effect is observed because petrol NH_3 emissions tend to increase as the vehicles age, and not because of regulatory changes, as this pollutant has never been regulatorily restricted.[15]

For diesel passenger cars, average NH_3 emissions are essentially zero for pre-Euro 6 vehicles, with an increasing trend for vehicles certified to Euro 6, 6d-TEMP and 6d standards. Typically, the fuel combustion process in a diesel engine does not lead to the formation of NH_3. However, exhaust aftertreatment technologies introduced to control NO_x emissions can lead to the formation and emission of NH_3 as an unwanted byproduct of the NO_x control process. One of these technologies, known as lean- NO_x trap, stores and de-stores NO_x, and may release NH_3 during those cycling events. Selective catalytic reduction systems are the most commonly used technology to meet the latest Euro 6d NO_x standards. These systems use NH_3 as a reducing agent to convert NO_x to N_2 over a catalyst. If the amount of NH_3 used in this process is poorly

15 Gary A. Bishop and Donald H. Stedman, "Reactive Nitrogen Species Emission Trends in Three Light-/Medium-Duty United States Fleets," *Environmental Science & Technology* 49, no. 18 (August 31, 2015): 11234–40, https://doi.org/10.1021/acs.est.5b02392.

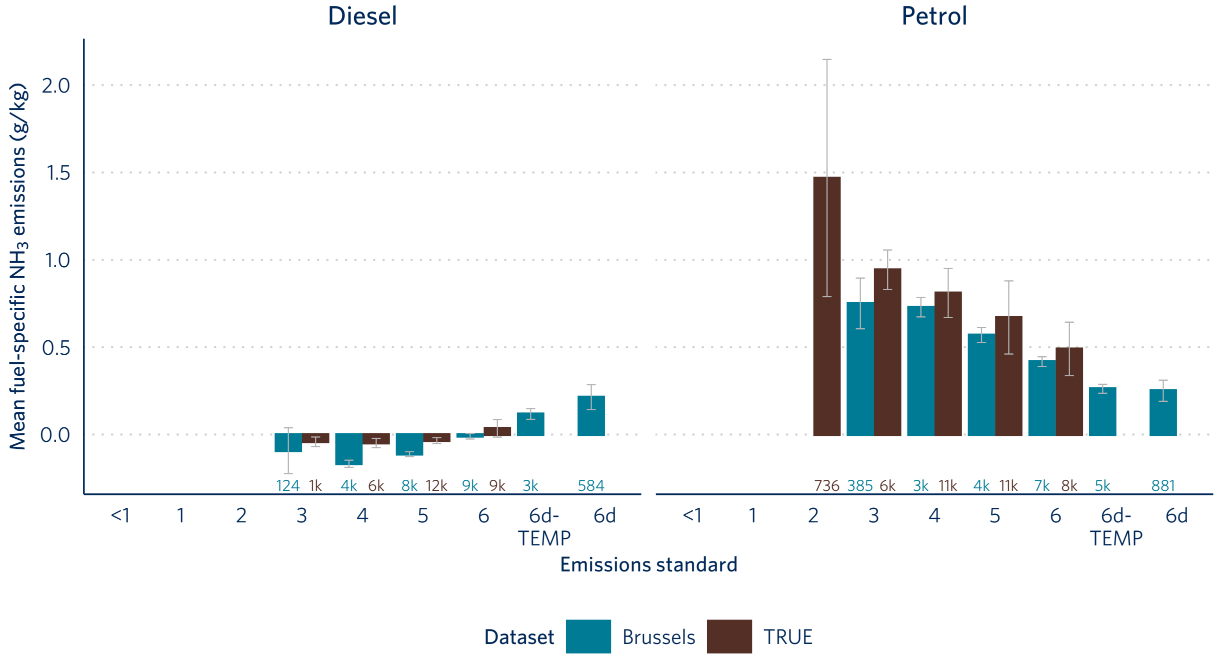


Figure 15. Mean fuel-specific NH_3 emissions from diesel and petrol passenger cars by emissions standard for Brussels and TRUE remote sensing data The number of measurements is presented below each bar. Only results for groups with at least 100 measurements are shown. Average negative emissions from pre-Euro 6 diesel vehicles are likely the consequence of the lack of a daily calibration of the instrument.

calibrated, it can lead to tailpipe NH_3 emissions, known as NH_3 slip. The measurements suggest that while latest emission standards for diesel passenger cars exhibit lower NO_x emissions, NH_3 emissions are approaching those of petrol equivalents.

LIGHT COMMERCIAL VEHICLE NITROGEN OXIDE EMISSIONS

Figure 16 presents the average fuel-specific NO_x emissions from LCVs by fuel type and emissions standard and compares the Brussels results with the TRUE reference data. The vast majority (97%) of LCVs in the Brussels dataset are diesel-powered, in line with sales statistics for Belgium. The average fuel-specific NO_x emissions of diesel LCVs show a similar trend to those of passenger vehicles, with pre-Euro 6 diesel LCVs having the highest NO_x emission levels. In this case, average fuel-specific NO_x emission factors for these groups were 2.3 times higher than Euro 6 diesel LCV emission levels and 5.9 times higher than those of Euro 6d-TEMP and 6d diesel LCVs. Although we do not present a direct comparison here, the observed NO_x emission factors measured for Euro 3–6 diesel LCVs indicate that the real-world emissions for these groups may exceed type-approval levels by several times, mirroring the findings for passenger cars. Diesel Euro 6d-TEMP LCVs show a 60% decrease in average NO_x emissions relative to Euro 6 diesels, but emissions from this group remain 2.2 times higher than Euro 6d-TEMP petrol LCVs. Petrol Euro 6 and Euro 6d-TEMP LCVs show little difference in their mean fuel-specific NO_x emissions.

Figure 17 shows the estimated share of LCV NO_x emissions for individual vehicle groups. Euro 5 diesel LCVs account for nearly half of the total NO_x emissions, a disproportionate amount relative to their estimated fleet share. Euro 4 and Euro 6 diesel vehicles account for most of the remaining NO_x emissions from LCVs operating in Brussels.

The current Brussels LEZ timetable for LCVs bans pre-Euro 6 diesel vehicles and pre-Euro 3 petrol LCVs starting in 2025. Our findings show that implementing these changes will remove LCV vehicle groups with the highest real-world NO_x emission factors from the streets of Brussels. Earlier action to move this implementation date forward, in particular for Euro 5 diesel LCVs, could accelerate expected emissions reductions. As was the case with passenger vehicles, the relatively high real-world NO_x emissions from pre-RDE Euro 6 diesel LCVs compared to RDE-compliant diesel LCVs supports the proposed LEZ implementation steps banning these vehicles. Brussels should therefore consider moving

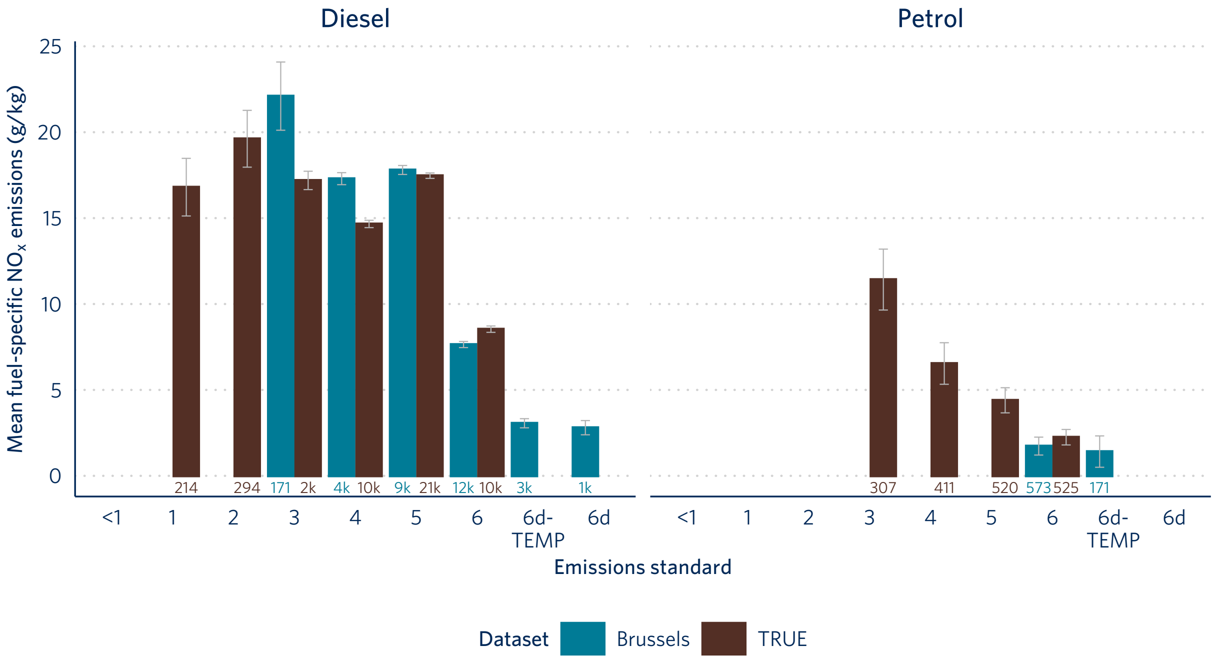


Figure 16. Mean fuel-specific NO_x emissions from diesel and petrol light commercial vehicles by emissions standard for Brussels and TRUE remote sensing data. The number of measurements is presented below each bar. Whiskers represent the 95% confidence interval of the mean. Only results for groups with at least 100 measurements are shown.

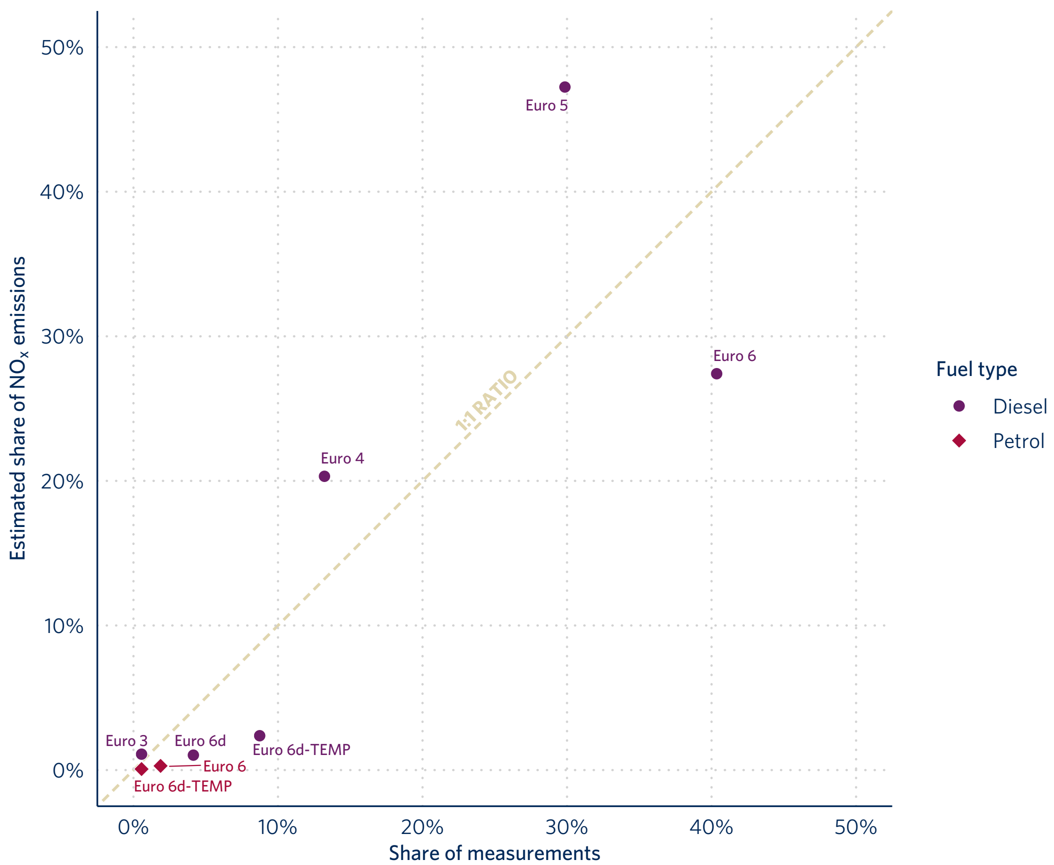


Figure 17. Share of measurements and estimated share of total NO_x emissions from light commercial vehicles in Brussels by emissions standard and fuel type. The share of remote sensing measurements is used as a proxy for vehicle-kilometers travelled by each group of vehicles.

this implementation step forward from 2028 to 2025 to address the high NO_x emissions from this group.

LIGHT COMMERCIAL VEHICLE PARTICULATE MATTER EMISSIONS

Figure 18 presents average fuel-specific PM emissions from light commercial vehicles. The average PM emissions of diesel LCVs show a clear downward trend from Euro 3 to Euro 5. We attribute the significant reduction in PM from Euro 4 to Euro 5 to the use of DPFs, which began with Euro 5. The mean fuel-specific PM emissions remain low for successive standards.

Emission results for petrol LCVs show significantly higher PM emissions for Euro 6 vehicles in Brussels compared to the reference TRUE dataset. We explored the Brussels data further and found that one third of the measurements in this category came from a single vehicle model—the Fiat Doblò equipped with a 1368 cc engine. As shown in Figure 19, the PM emissions for this vehicle model significantly exceeded those of other petrol Euro 6 LCVs measured in Brussels. The average PM emission factor, 0.67 g/kg, is similar to that observed for diesel Euro 4 LCVs and an order of magnitude greater than the average emission factor for the remaining petrol Euro 6 LCVs in the Brussels dataset. The Fiat Doblò uses an indirect injection engine, which means it is not subject to tailpipe PM and PN emission standards.

The real-world emissions of indirect injection petrol LCVs warrant further scrutiny. Left unregulated, these vehicles may become an increasingly significant source of PM emissions, since the widespread application of particulate filters control the PM emissions from diesel and direct injection petrol LCVs. The Euro 7 regulation now under development, which will likely set fuel and technology-neutral PM and PN limits, is expected to close this loophole. However, these limits will only apply to new vehicles starting in the 2025–2027 timeframe. Under the current LEZ implementation schedule, Brussels will allow high-emitting Euro 6 petrol LCVs to operate in the city until 2030.

Figure 20 shows the estimated share of PM emissions for individual LCV groups. Similar to findings for passenger cars, Euro 4 diesel vehicles contribute the largest share of LCV PM emissions, followed by Euro 5 and 6 diesels. The next phase of the Brussels LEZ, which will extend access restrictions to Euro 4 diesel LCVs, should significantly reduce the average emissions of LCVs operating in the city.

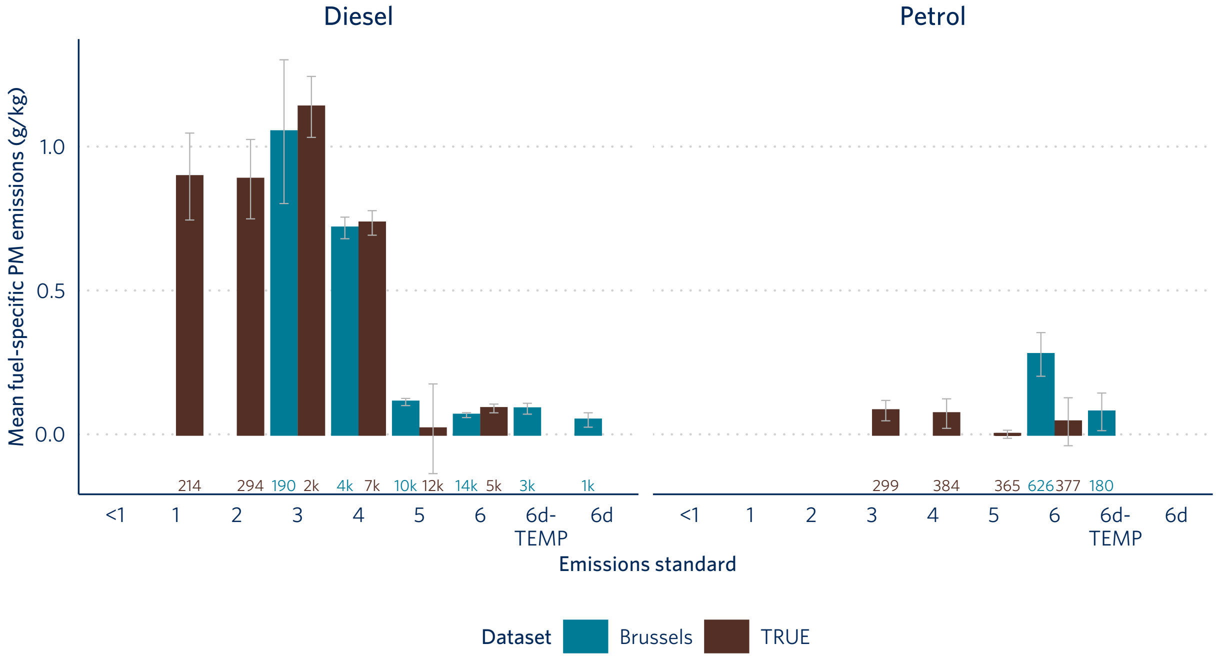


Figure 18. Mean fuel-specific PM emissions from diesel and petrol light commercial vehicles by Euro standard for Brussels and TRUE remote sensing data. The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean. Results are only shown for groups with at least 100 measurements.

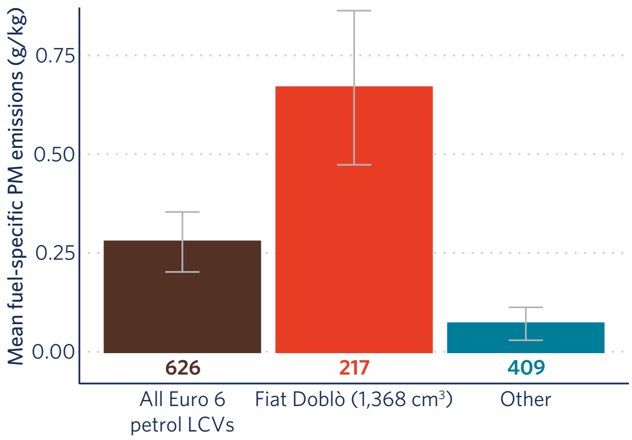


Figure 19. Mean fuel-specific PM emissions from Euro 6 petrol light commercial vehicles measured in Brussels compared to the Fiat Doblò using the 1,368 cm^3 petrol engine and other Euro 6 petrol light commercial vehicles. The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean. Only results for groups with at least 100 measurements are shown.

TAXIS AND RIDE-HAILING EMISSIONS

This section presents findings from the TRUE Brussels study on the emissions of taxi and ride-hailing vehicles. In Brussels, these vehicles can easily be identified by the formats of their license plates: Plates for taxis start with TX, and those for ride-hailing vehicles start with TL. The Brussels dataset contained 2,222 measurements of taxis from 726 unique vehicles and 3,341 measurements of ride-hailing vehicles from 1,144 unique vehicles. The collected sample of taxis was fairly representative of the Brussels taxi fleet, constituting 58% of all taxis registered in Brussels. The number of ride-hailing vehicles exceeded the number of those registered in the city (1,081), likely because some of the measured vehicles were registered elsewhere. For our analysis, we group taxis and ride-hailing vehicles together, as their respective average total NO_x and PM emissions factors are comparable. Altogether, the measurements of these vehicles made up 2.7% of total passenger car measurements.

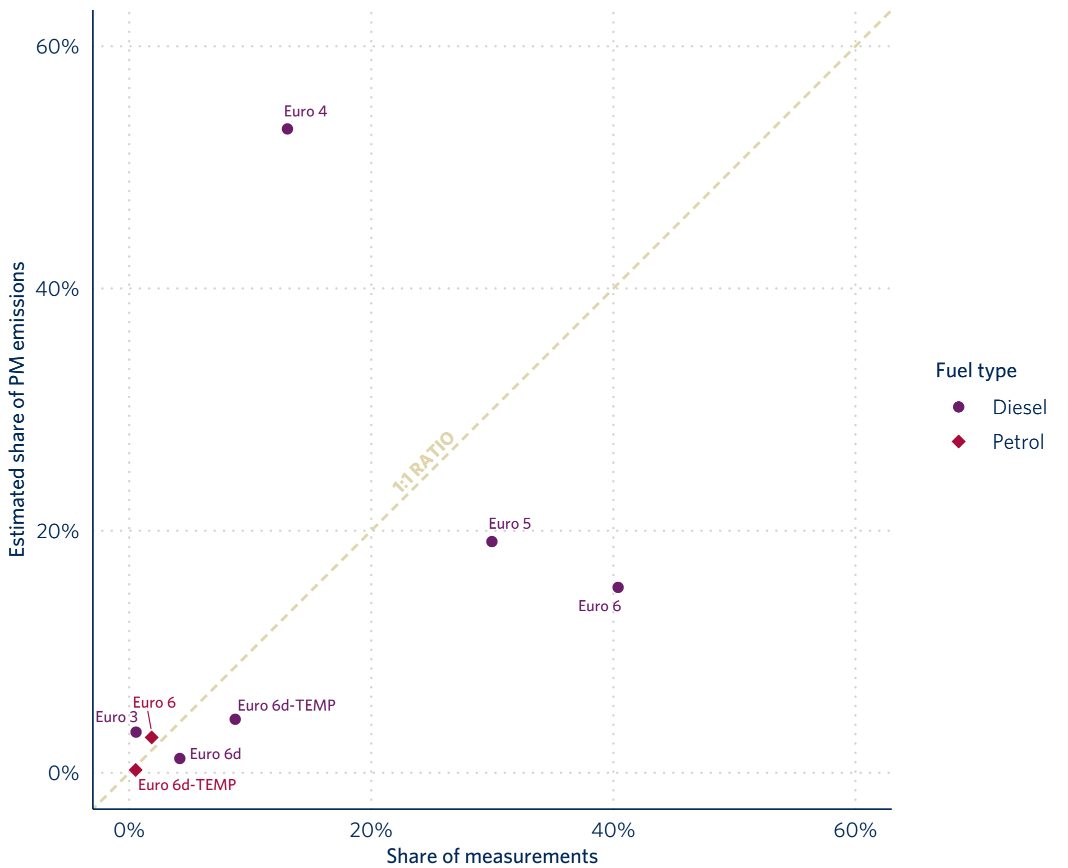


Figure 20. Share of measurements and estimated share of total PM emissions from light commercial vehicles in Brussels by emissions standard and fuel type. The share of remote sensing measurements is considered as a proxy of vehicle-kilometers travelled by each group of vehicles.

Figure 21 shows the fleet composition of the taxi and ride-hailing fleet, compared with that of other passenger cars. Passenger cars excluding taxis and ride-hailing vehicles are distributed across both fuel types and emission standards from Euro 4 to 6d. Most (95%) of the taxi and ride-hailing fleet in Brussels is diesel-powered, which may be explained by the historically lower operating costs of diesel vehicles. Euro 6 diesels account for more than half (57%) of the total taxi and ride-hailing vehicle measurements, followed by Euro 5 diesels (20%) and Euro 6d-TEMP diesels (9%). Euro 6 is the most common standard for petrol vehicles, but this group comprises only around 5% of the total taxi and ride-hailing fleet. There are no pre-Euro 5 taxis in the dataset, as the city of Brussels requires that all operating taxis and ride-hailing vehicles must not be older than 7 years.

Figure 22 presents mean fuel-specific NO_x and PM emission factors for the taxi and ride-hailing fleet by emissions standard and fuel type and compares them to similar data for passenger cars measured in Brussels. On average, the NO_x emissions of taxi and ride-hailing vehicles in Brussels are 21% greater than those of other passenger cars. We attribute this difference primarily to the much higher share of diesel vehicles in the taxi and ride-hailing fleet. The average NO_x emissions for Euro 6 diesel vehicles, the most common taxi and ride-hailing vehicle type, are 1.2 to 4.7 times higher than the average emissions of petrol passenger vehicle groups. Although the average NO_x emissions of diesel Euro 3 and 4 are higher than those of diesel Euro 6, the measurement shares of these standards for passenger vehicles are small. The diesel Euro 5 taxi and ride-hailing fleets show both a higher average emissions level and a larger share in measurements, which further contributes to the overall emissions regardless of fuel type.

Average PM emission factors for taxis and ride-hailing fleet are 33% lower than those of other passenger cars, primarily due to the greater share of non-DPF-equipped pre-Euro 5 diesel vehicles in the passenger car fleet. Euro 6 diesel vehicles, which make up most of the taxi and ride-hailing fleet, have relatively low average PM emissions factors. Because of the city's requirement that limits the operation of taxis of over 7 years, nearly all taxis or ride-hailing cars in Brussels were certified to Euro 5 or newer standards. In contrast, pre-Euro 5 diesel vehicles accounted for approximately 10% of the passenger car fleet and, as discussed above, disproportionately contributed to total PM emissions from this group. These differences in the fleet distribution and the impacts of non-DPF-equipped vehicles in the passenger car fleet led to the lower average PM average emission factor observed for taxis and ride-hailing vehicles than that of other passenger cars.

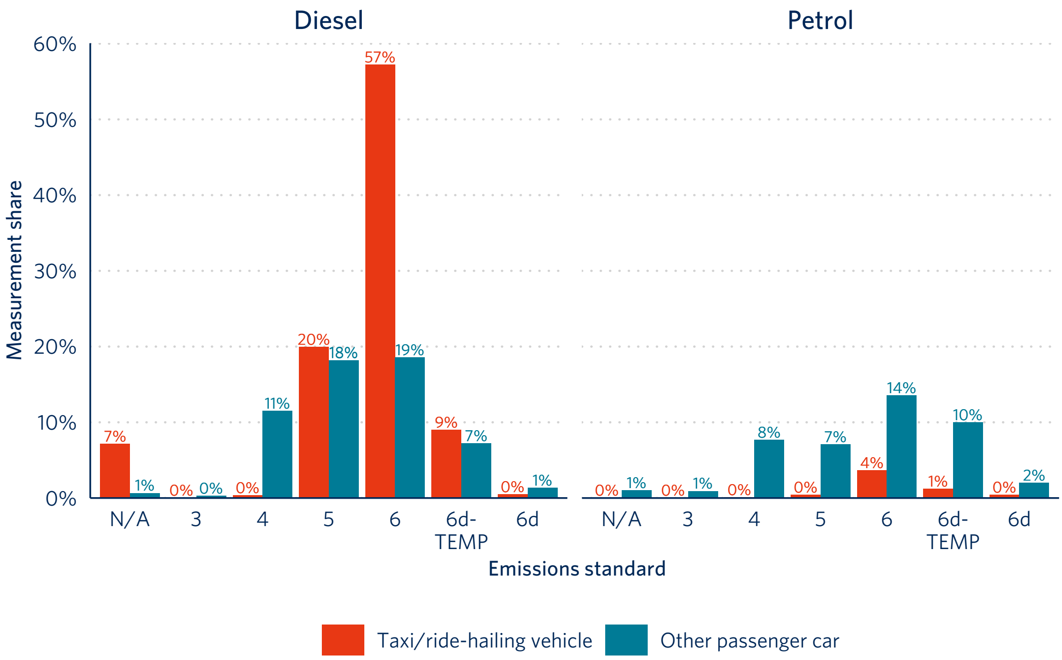


Figure 21. Comparison of Brussels taxi and ride-hailing and other passenger car measurements by fuel type and emissions standard. N/A indicates that no Euro standard could be identified.

Figure 22. Mean fuel-specific NO_x and PM emissions (g/kg) from Brussels taxis and ride-hailing vehicles and other passenger cars by fuel type and emissions standard. The number of measurements is presented under each bar. Whiskers represent the 95% confidence interval of the mean.

Our analysis implies that Brussels can anticipate a substantial reduction in NO_x emissions from phasing out diesel Euro 5 taxis and ride-hailing vehicles, which show the highest average emission factor. Brussels' 7-year age limit for taxis will be highly effective in this regard because it will ban Euro 5 by the end of 2022 —over 2 years earlier than the LEZ requires for all passenger cars in Brussels. However, with the same age limit, pre-RDE diesel Euro 6 taxis and ride-hailing vehicles will still be allowed to operate up to late 2026. The elevated real-world NO_x emissions from this group, their prevalence in the taxi and ride-hailing fleets, and the relatively high usage rates for these vehicles, may warrant further actions to spur replacement with vehicles that have demonstrably low real-world emissions. For example, Brussels could set Euro 6d LEZ requirements for taxis and ride-hailing vehicles ahead of implementation for the broader passenger vehicle fleet scheduled for 2028, or require that all newly registered taxi and ride-hailing vehicles be zero-emission-capable (i.e., be plug-in vehicles with a substantial zero-emission range), or zero-emission. Some cities such as London have already implemented the latter policy.[16]

BUS EMISSIONS

This section focuses on buses measured in the Brussels remote sensing campaign. All of these buses were diesel-powered. A total of 2,829 measurements were obtained from 458 unique buses. Around 90% of all buses were type-approved to Euro VI, with Euro V constituting most of the remaining sample. Emission standards of less than 2% of the buses were either missing or could not be identified. We classified two different types of buses based on the number of seats and the model: transit bus (19–30 seats) and coach (31 or more seats). The analysis focuses on transit and coach buses, as they constituted 99% of the measurements. The other 1% consisted of vans and

16 Peter Slowik, "Can London Be a Model for Zero-Emission Mobility?," *ICCT Staff Blog*, October 1, 2018, https://theicct.org/blog/staff/can-london-be-model-for-zero-emission-mobility.

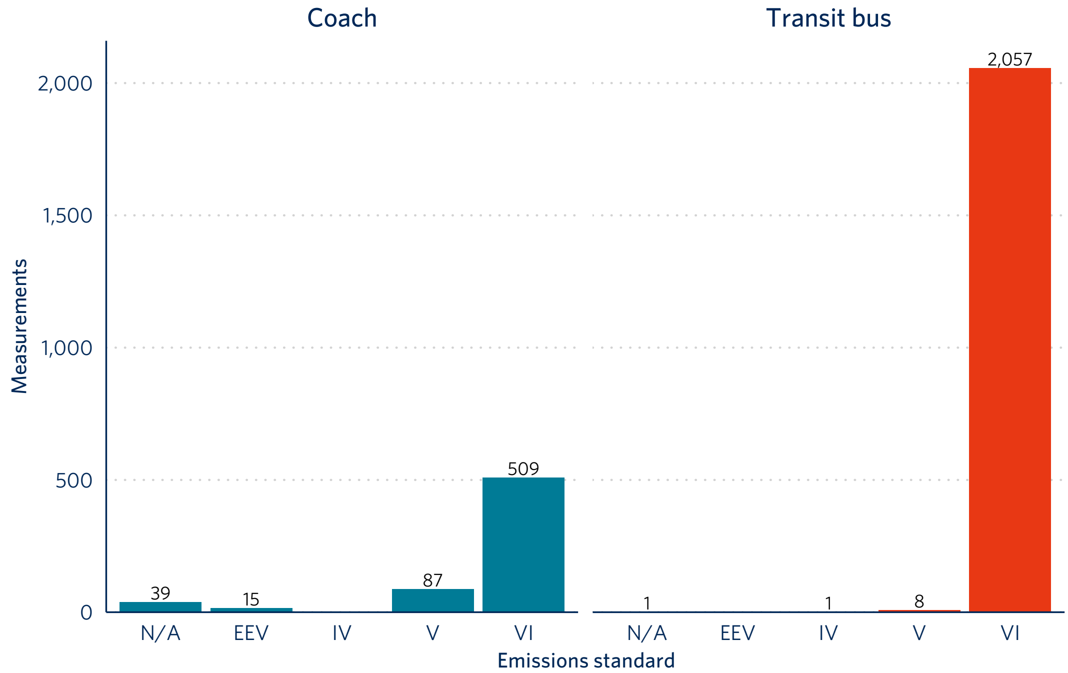


Figure 23. Number of bus measurements by emissions standard and bus type. Buses with unidentifiable emissions standard are expressed as N/A. EEVs refer to "enhanced environmentally friendly vehicles," vehicles with voluntary, strincter emission limits.

minibuses. Coach and transit buses typically serve different purposes. Coaches cover longer distances and often operate between cities or regions and for private charter, while transit buses make frequent stops on predetermined routes. We assume that STIB operates all transit buses measured during this campaign .

Figure 23 shows the number of bus measurements in Brussels by emissions standard and bus type. The majority (73%) of the bus measurements in Brussels consists of diesel Euro VI transit buses, followed by Euro VI (18%) and Euro V coaches (3%).[17] Researchers took very few measurements of Euro IV and Euro V transit buses even though, according to fleet information from STIB obtained a few months after the remote sensing campaign (April 2021), these buses represented respective shares of 16% and 29% of the transit bus fleet.

Figure 24 shows the average emissions of NO_x and PM for all coach and transit buses by emissions standard and bus type. Generally, NO_x and PM emissions are significantly lower for Euro VI than Euro V. Euro V coaches in Brussels have average NO_x emissions almost 6 times the emissions of Euro VI coaches and average PM emissions that are 4.5 times the emissions of Euro VI coaches.

For context, it is possible to convert the regulatory energy-specific limit, expressed in g/kWh, to fuel-specific units in g/kg. Other researchers have developed a conservative method based on the transient testing emissions limit for Euro VI (0.46 g/kWh), the on-road conformity factor of 1.5 set in the regulation, and a generously high engine efficiency (40%).[18] With these assumptions, the Euro VI on-road limit of 0.69 g/kWh would be 3.2 g/kg when converted to fuel-specific units. The average level of NO_x emissions of all Euro VI buses in Brussels shows a level likely to exceed this value (7.8 g/kg). When comparing different bus types, Euro VI transit buses show the highest average NO_x emissions (9.0 g/kg), a level that is more than double that of Euro VI coaches (3.6 g/kg).

In order to investigate further the difference in NO_x emissions between Euro VI coaches and transit buses, we break the sample down to pre-Euro VI-D and Euro VI-D vehicles. The implementation stage of Euro VI-D requires vehicles to pass a more stringent in-service conformity test that includes on-road testing at lower

17 Due to an insufficient samples size of only 20 unique vehicles, we do not distinguish hybrid buses as a separate vehicle group in this analysis.

18 Denis Pöhler et al., "Remote RDE Messtechnik Validierung," accessed October 2, 2021, https://www.aramis.admin.ch/Default?DocumentID=61263&Load=true.

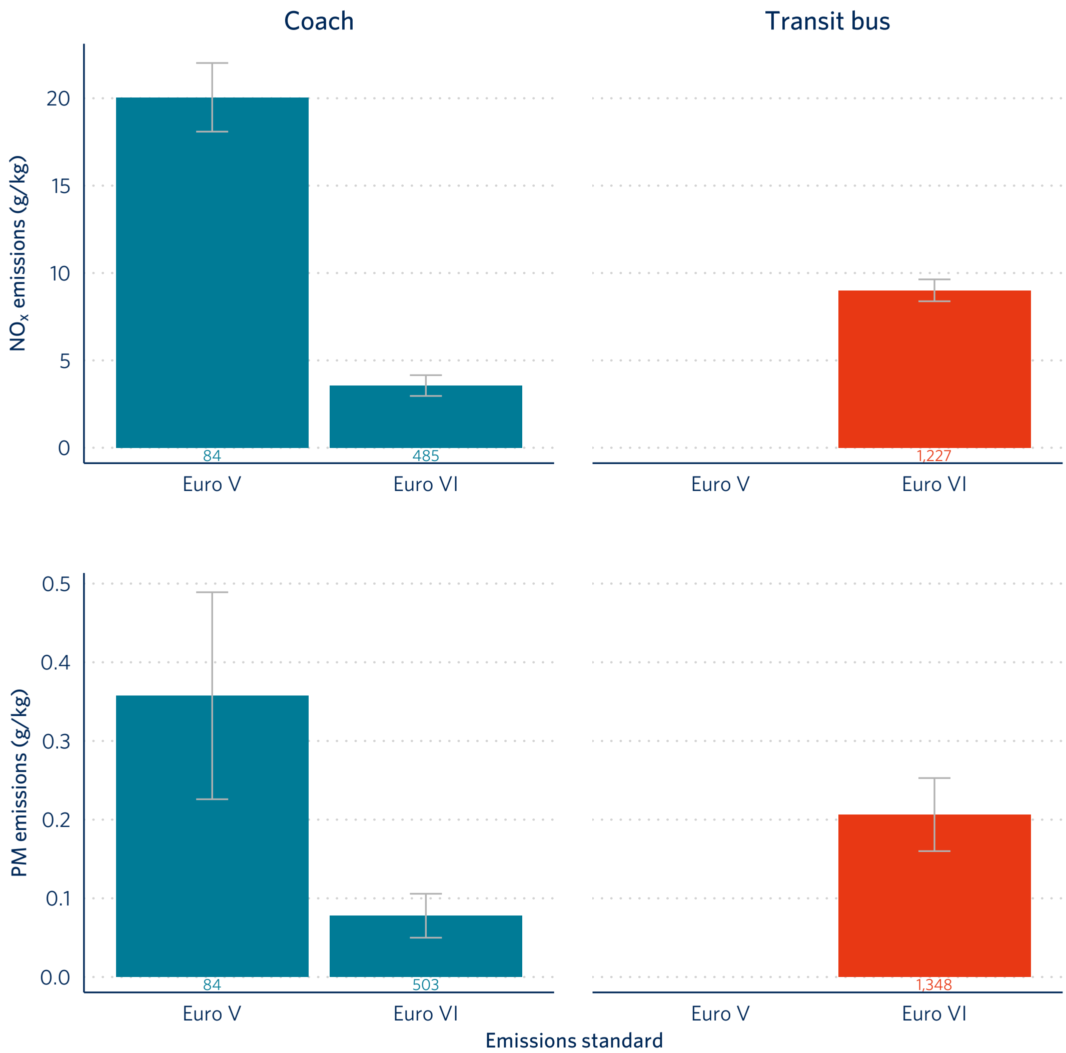


Figure 24. Fuel-specific NO_x and PM emissions of coaches and transit buses by emissions standard. Only results for groups with at least 20 measurements are shown.

engine power that is characteristic of urban conditions. As a result, vehicles equipped with engines certified to these standards are expected to emit less in real-world settings. We conservatively assume that Euro VI-D vehicles were registered after September 2019, the time at which all newly registered vehicles had to comply with the standard. We categorized Euro VI buses registered prior to the date as pre-Euro VI-D. Euro VI coaches appear to have lower emissions than Euro VI transit buses because more coaches are type-approved to Euro VI-D. Figure 25 confirms that, on average, Euro VI-D buses perform significantly better (1.6 g/kg) than pre-Euro VI-D buses (4.8 g/kg for coaches and 9.0 g/kg for transit buses) and are likely to meet the NO_x on-road limit of 3.2 g/kg for Euro VI in urban conditions. Although the poorer performance of pre-Euro VI-D transit buses relative to pre-Euro VI-D coaches merits further investigation, the observed emissions performance of Euro VI-D vehicles suggests that increasing the share of Euro VI-D transit buses can significantly lower the overall NO_x emissions of transit buses in Brussels.

We further assess the NO_x emissions performances of pre-Euro VI-D and Euro VI-D coach and transit buses by manufacturer. Transit buses were mostly manufactured by Mercedes (83%), followed by Van Hool (15%), and consisted exclusively of buses certified to pre-Euro VI-D. Four companies —Iveco, Mercedes, Van Hool, and VDL —manufactured 87% of coaches measured in Brussels. A significant number of vehicles certified to Euro VI-D and above were Mercedes vehicles and accounted for 70% of the Mercedes coach fleet.

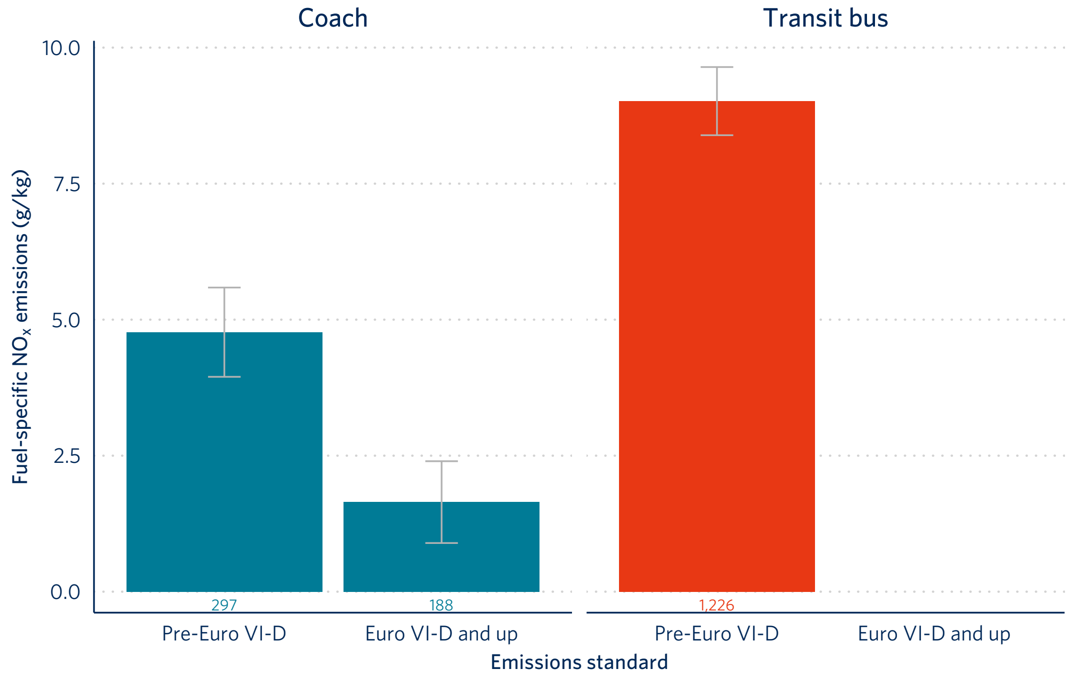


Figure 25. Comparison of average NO_x emissions of coach pre-Euro VI-D, coach Euro VI-D and up, and transit bus pre-Euro VI-D. Only results for groups with at least 30 measurements are shown.

Overall, coaches appear to perform better than transit buses, although their average NO_x emissions vary across manufacturers. Figure 26 demonstrates that, despite their relatively low average NO_x emissions compared to transit buses, only Iveco coaches certified to pre-Euro VI-D (1.7 g/kg) and Mercedes coaches certified to Euro VI-D and above (1.3 g/kg) show NO_x emission factors under the calculated NO_x limit of 3.2 g/kg. Transit buses of both manufacturers show levels of average NO_x emissions that are likely to exceed the calculated NO_x limit. Mercedes transit buses, all of which were considered pre-Euro VI-D, perform much worse (9.3 g/kg) than their coach counterparts, emitting over 7 times the NO_x level of buses certified to Euro VI-D and above and almost times that of pre-Euro VI-D. Both coaches and transit buses manufactured by Van Hool show similar levels of average NO_x emissions, likely because nearly all measurements obtained were

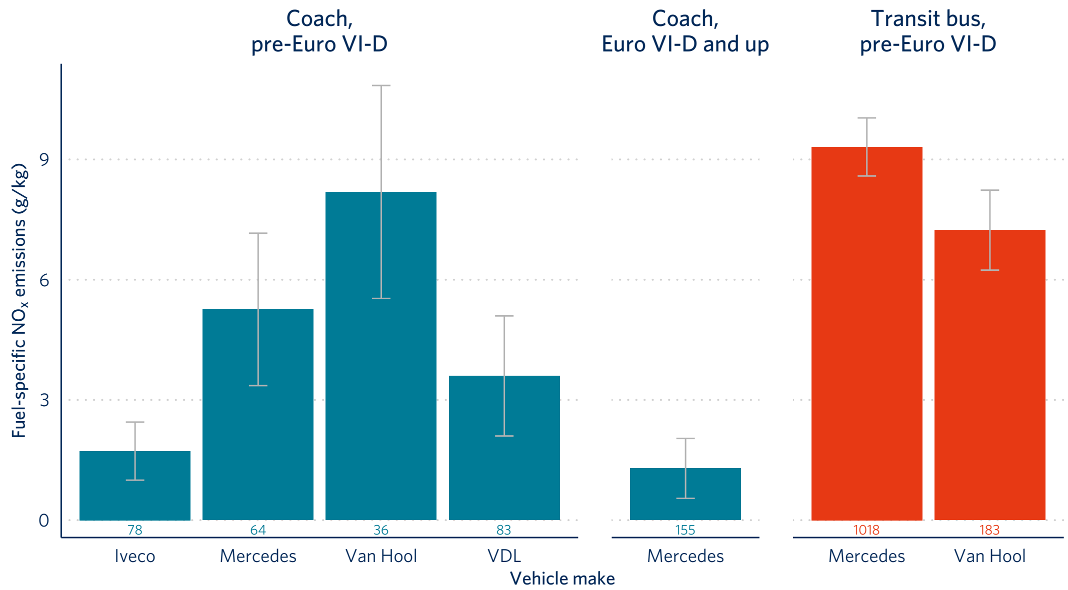


Figure 26. Average NO_x emissions of Euro VI coaches and transit buses by manufacturer. Only results with at least 30 measurements are shown.

of pre-Euro VI-D. However, this analysis is only based on eight unique Van Hool buses, and more conclusive evidence is necessary to determine Van Hool buses' emissions performance.

This analysis reveals that transit buses in Brussels emit more NO_x emissions than coach buses and that further policies to address the emissions from this high-usage fleet could help to reduce NO_x emissions in Brussels. The proposed implementation timeline for the Brussels LEZ requires all buses to meet, at a minimum, Euro VI-D standards beginning in 2028 and to be zero-emission by 2036. While these are important steps, the real-world emissions results make clear the emissions benefits of Euro VI-D-certified buses relative to previous implementation steps of the Euro VI standard. The results suggest that any new buses entering the STIB fleet should be certified to at least Euro VI-D standards. However, given the currently available technology and the city's long-term LEZ targets, we recommend that all transit buses transition to zero-emission alternatives, such as electric options, to deliver the greatest emission reductions across all pollutants.

TAILPIPE PARTICLE NUMBER MEASUREMENT CAMPAIGN

In 2009, the Euro 5 emissions standard introduced a new PM emissions limit of 5 mg/km for diesel passenger cars—significantly more stringent than the former Euro 4 limit of 25 mg/km. DPFs were widely adopted to comply with the more stringent standard. From September 2011, the Euro 5b legislation introduced a PN emissions limit in addition to mass-based limits. A solid PN type-approval limit of 6×10^{11} per kilometer became effective for all categories of light-diesel vehicles. Vehicles must meet the PN limit in addition to the PM mass emission limits. Since January 2012, every new diesel passenger car and LCV registered in the EU has been equipped with a DPF. When operating as designed, DPFs typically reduce PM mass emissions by over 95% and PN emissions by over 99%. However, if a DPF malfunctions or is intentionally removed, PM mass and PN emissions can increase significantly—by as much as 15 to 50 times for PM mass and several orders of magnitude for PN—relative to the emissions from the same model vehicle with a properly functioning DPF.[19] Identifying and addressing instances where DPFs are not performing effectively are critical steps to ensuring the emissions control benefits that these technologies offer are realized.

The TRUE Brussels study included a three-day campaign to measure the tailpipe PN concentrations of light-duty vehicles to investigate how PN instruments can combine with remote sensing techniques to develop methods for screening highly emitting vehicles. We analyzed data collected during this study to evaluate the prevalence of DPF tampering or malfunction and to provide evidence to support ongoing discussions regarding the inclusion of PN testing in the Belgian Periodic Technical Inspection (PTI) program.

During the three days of testing, field technicians used a TSI 3795 PN instrument to measure the PN concentration at the tailpipe of close to 600 vehicles, including 312 light-duty diesel vehicles.[20] Technicians pulled vehicles over to the roadside and asked their drivers to participate in the study on a voluntary basis. Engines were placed in idle, and researchers attached the probe to the tailpipes of the vehicles. Each test lasted for about 30 seconds. The instrument sampled PN concentrations at a frequency of 1 Hz and we calculated the average tailpipe concentration using all 30 datapoints.

The PN measurement is more sensitive than traditional opacity-based measurements of PM emissions used in PTI programs and is better suited to identify instances of poor DPF performance or removal. The unit researchers used during the campaign was able to measure fine and ultrafine particles concentration from 1,000 to 10,000,000 particles per cubic centimeter, with sizes between 23 and 1000 nanometers. In early 2021, the Netherlands, Germany, and Belgium approved the use of this type of instrument to replace the outdated smoke test for the inspection of diesel vehicles equipped with DPFs.

Figure 27 presents the details of the vehicles tested during the PN emissions study. The majority of vehicles were passenger cars (73%). LCVs represented 17% of all tests. Nearly all LCVs and the majority of the passenger cars were diesel, consistent with the fleet characteristics observed during the main remote sensing campaign. However, the shares of Euro 6,

19 Nils Hooftman, "Tampering," (uCARe, December 19, 2019,) https://www.project-ucare.eu/wp-content/uploads/2020/01/D1.3-Tampering-.pdf.

20 TSI, "Nanoparticle emission tester model 3795," accessed October 2, 2021, https://tsi.com/products/particle-counters-and-detectors/engine-exhaust-particle-counters/nanoparticle-emission-tester-model-3795/.

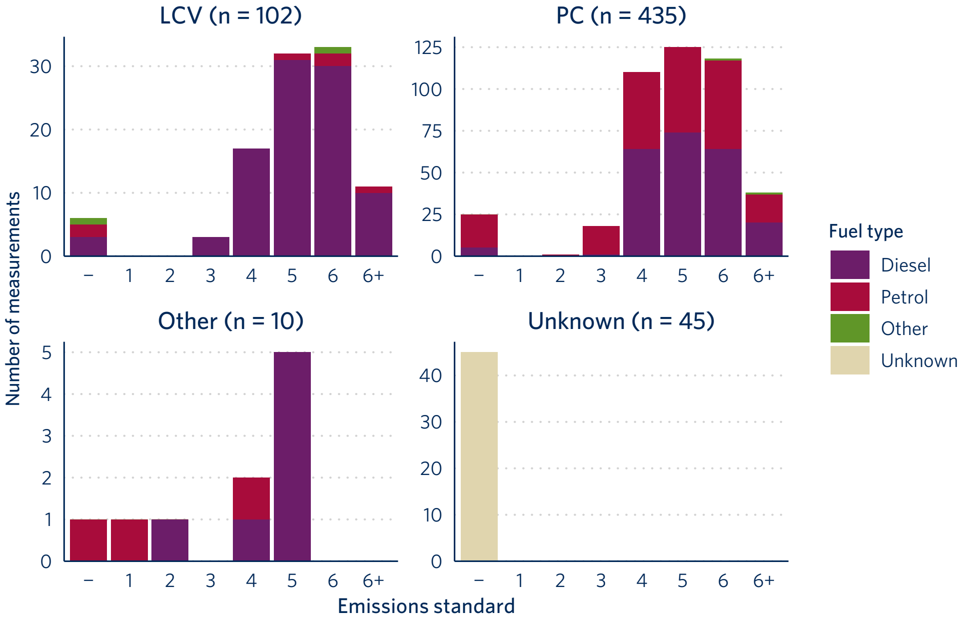


Figure 27. Number of particulate number measurements by vehicle class, estimated emissions standard, and fuel type. 6+ refers to the Euro 6d-TEMP and 6d emission standards. Dashes (–) represent unknown values.

Euro 6d-TEMP, and 6d vehicles are comparably lower in the PN testing sample. This can likely be explained by the testing location, which was situated on a street directly leading to a PTI inspection facility. In Belgium, new vehicles are exempt from PTI requirements for the 4 years following their first registration, unless they are sold during this period. Following this period, the vehicles must undergo annual inspections. As a result of these requirements, the location of the testing at a street leading to a PTI facility likely skewed our sample toward older vehicles relative to the on-road fleet distribution in Brussels.

Figure 28 presents the measured PN tailpipe concentration for light-duty vehicles by Euro standard. The upper panel shows results for diesel vehicles, while the lower panel shows results for petrol vehicles. We group results for passenger cars and LCVs, as these vehicle groups have identical PN emission limits from Euro 5b onwards. It is important to note that the tailpipe PN concentrations of diesel and petrol vehicles measured in this manner are not directly comparable.[21]

Results show pre-Euro 5 vehicles to be the worst performing diesel group. This group had a median PN concentration above 8 million particles/cm^3, and 91% of the tested vehicles had tailpipe concentrations above 1 million particles/cm^3. Pre-Euro 5 diesel vehicles are known to have high PM mass emissions, and these findings confirm high PN emissions for this group. The findings also provide further evidence in support of the next implementation stage of the Brussels LEZ, which bans Euro 4 diesel vehicles beginning in 2022, and indicate that this step will provide important PN emissions benefits.

Diesel vehicles originally equipped with DPFs show highly skewed results. Euro 5 vehicles have a median particle concentration almost 100 times lower than the average. Among the newest vehicles, one diesel 6d-TEMP vehicle registered in December 2019 had a tailpipe PN concentration that exceeded the upper measurement limit of the instrument, 10 million particles/cm^3. Because it is less likely for relatively new vehicles to have tampered emission control systems, it is possible that such a high PN level might be related to a damaged DPF or a manufacturing issue. These results indicate that newer diesel vehicles tend to be cleaner, but that high emitters are disproportionally increasing the average to multiple times the expected level with functioning DPFs.

Results for petrol light-duty vehicles show that pre-RDE Euro 6 vehicles exhibited the highest tailpipe PN concentrations. The average PN level for this group was 2.5 times the level of pre-Euro 5 vehicles and 3 times the level of Euro 5 vehicles. The higher

21 The combustion of diesel fuel occurs in excess of air, while petrol vehicles require an air-to-fuel mixture close to ideal to combust that can be an order of magnitude lower in idling operation. For a petrol and a diesel vehicle measured with the same pollutant concentration at engine idle, the rate of pollutant emissions into the atmosphere by the petrol vehicle might be an order of magnitude lower.

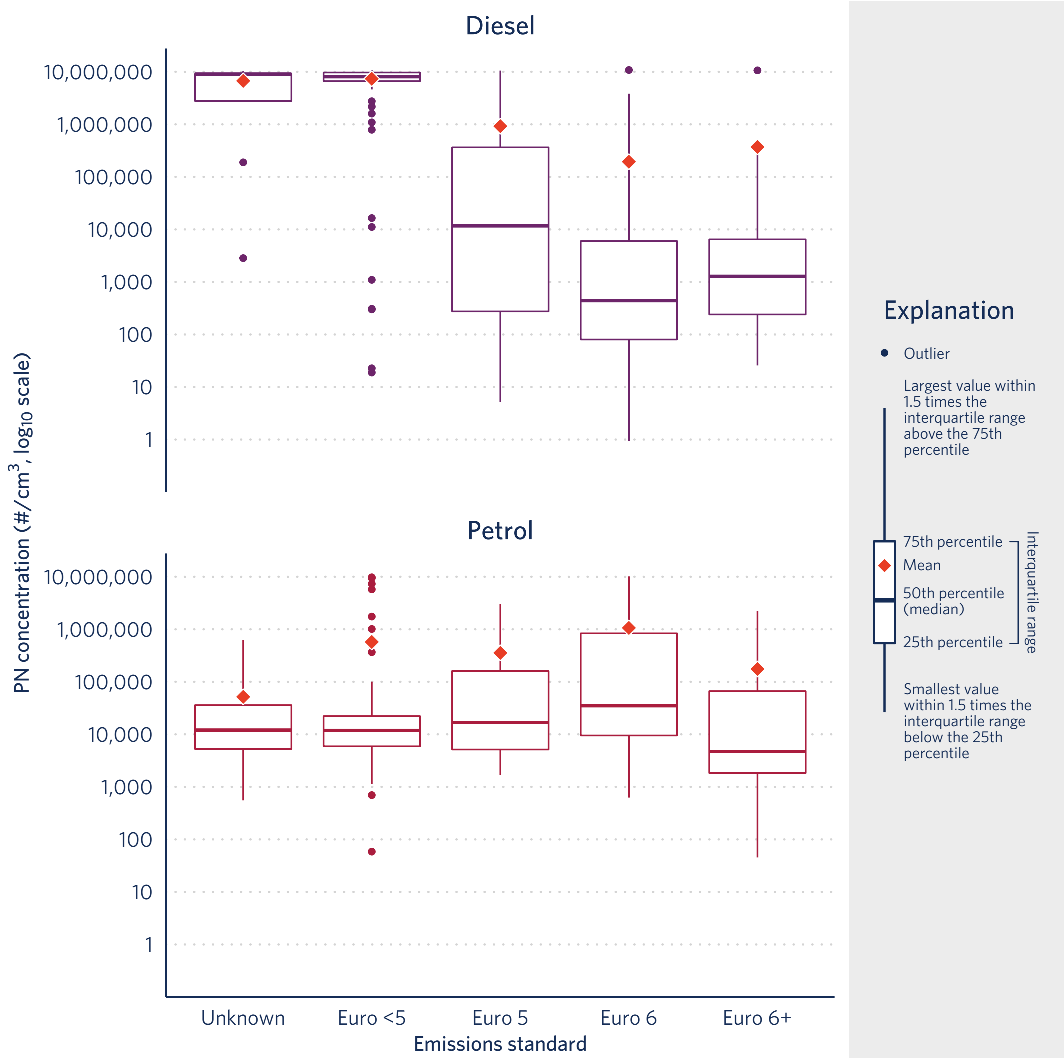


Figure 28. Boxplot of PN tailpipe emission concentration of light-duty vehicles by Euro standard and fuel type. Diamonds represent the mean emissions. Euro 6+ refers to Euro 6d-TEMP and Euro 6d.

concentrations observed for pre-RDE Euro 6 vehicles are likely related to the increasing market share of direct injection engines, which are designed to reduce CO_2 emissions but can lead to higher PN emissions. These vehicles represented about 8% of petrol passenger car sales until 2008, and around 90% in 2018.[22] Although the Euro 6 standard introduced a type-approval PN limit for petrol vehicles from September 2014, the regulation restricted its application to direct injection engines and established a 3-year derogation during which manufacturers could request to use a limit 10 times higher than for equivalent diesel vehicles. However, petrol vehicles certified to the RDE regime (6d-TEMP and 6d) show a clear emissions reduction that is, on average, 6 times lower than previous Euro 6 stages. We attribute this improvement to the phase-out of the derogation, which aligned the PN limit for petrol direct injection with the limit for diesel vehicles, as well as the introduction of the on-road type-approval, during which vehicles must emit less than 1.5 times the Euro 6 limit. These regulatory improvements drove the introduction of particulate filters for direct injection petrol vehicles. Although our measurements from these latest vehicles confirm lower emissions on average, they also suggest that some highly emitting vehicles are still present. In particular, petrol vehicles equipped with indirect injection engines are still exempt from any PM or PN limit, although in some cases these vehicles can have emissions exceeding those from for direct injected

22 Peter Mock, ed., *European Vehicle Market Statistics—Pocketbook 2020/21* (ICCT: Berlin, 2020), http://eupocketbook.org/.

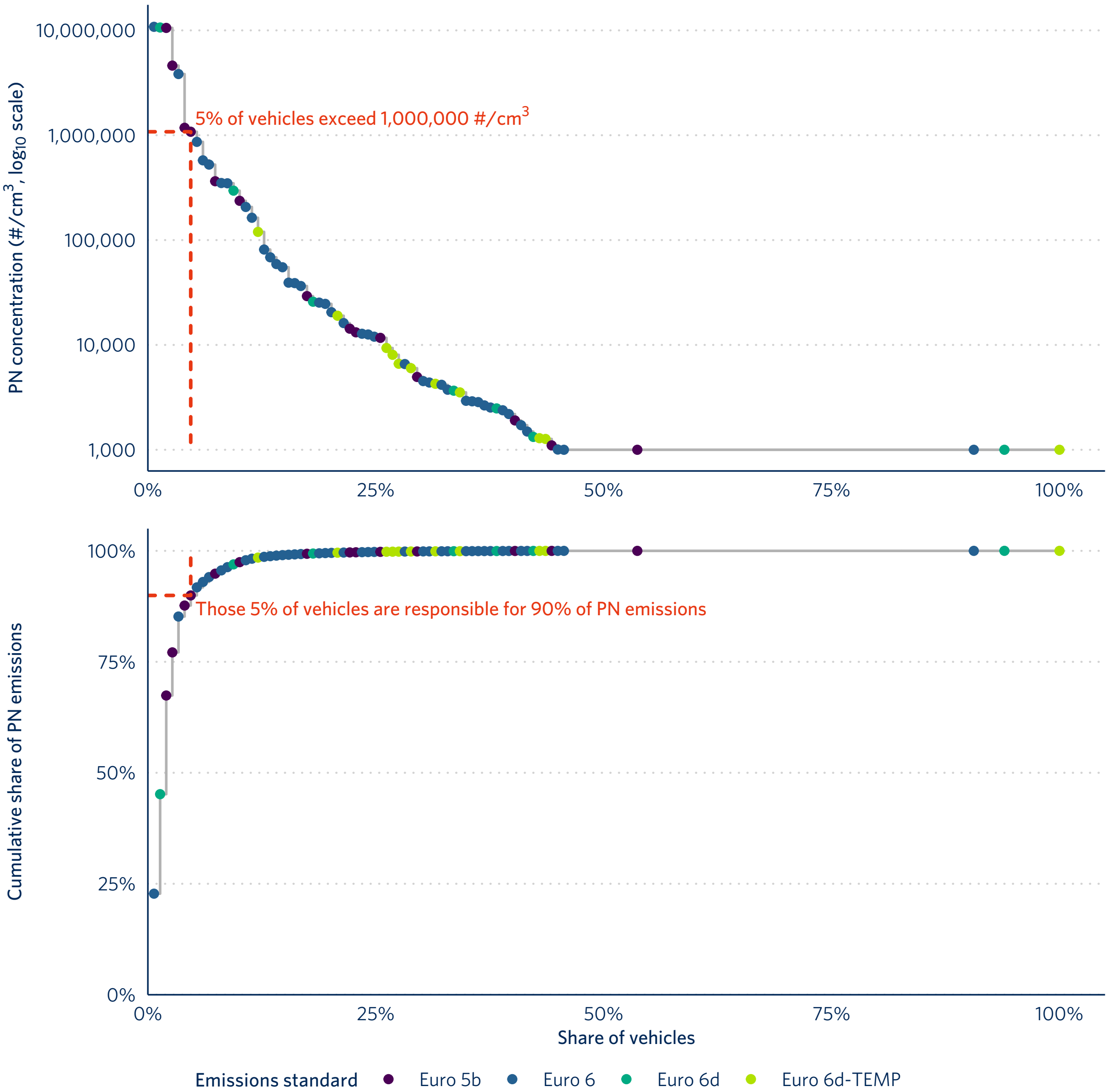


Figure 29. Distribution (upper panel) and cumulative share (lower panel) of light-duty diesel Euro 5b and 6 particle number tailpipe emission concentrations. Tests were conducted at idle. Particle number concentrations below 1,000 particles/cm^3 are artificially set to 1,000 particles/cm^3, corresponding to the low sensitivity range of the instrument.

engines.[23] The EU is currently preparing the next stage of light-duty vehicle standards, Euro 7, which is expected to close this loophole and be the first technology-neutral regulation setting common PM and PN limits for all passenger cars.

Previous studies have investigated the correlation between the laboratory test limit and the tailpipe concentration of diesel light-duty vehicle measured at idle.[24] Researchers found a 97.5% chance that vehicles with PN concentrations measured above 1,000,000 particles/cm^3 during the idle test would exceed the type-approval limit by around 5 times—a strong indication of DPF malfunction or tampering.

Figure 29 presents the PN concentration from light-duty diesel vehicles subject to a type-approval PN limit

23 Barouch Giechaskiel et al., "European Regulatory Framework and Particulate Matter Emissions of Gasoline Light-Duty Vehicles: A Review," *Catalysts* 9, no. 7 (July 2019): 586, https://doi.org/10.3390/catal9070586.

24 François Boveroux et al., "Impact of Mileage on Particle Number Emission Factors for EURO5 and EURO6 Diesel Passenger Cars," *Atmospheric Environment*, September 29, 2020, 117975, https://doi.org/10.1016/j.atmosenv.2020.117975.

(i.e.,Euro 5b and newer) and indicates the fraction of vehicles measured above 1,000,000 particles/cm^3 and their share of total PN emissions.

The results of this campaign show that about 5% of tested light-duty diesel Euro 5b and 6 vehicles had tailpipe PN concentrations greater than 1,000,000 particles/cm^3. This PN emissions level indicates the vehicle exceeds its type-approval limit by several times, likely due to malfunctions or intentional tampering of emissions control equipment. We estimated this small group of very high-emitting vehicles to be responsible for more than 90% of total particles emitted from all of the tested Euro 5b and 6 diesel vehicles. On March 24, the three Belgian regions agreed to implement DPF vehicle inspections using this method by July 2022 at the latest.[25] These results confirm that such polices targeting the highest emitters could significantly benefit emissions reduction in the fleet.

Another goal of the PN testing campaign was to develop new methods for screening highly emitting vehicles, such as by combining tailpipe PN concentration measurement with remote sensing. The two measurement methods fundamentally differ in their approach to characterizing particulate emissions from motor vehicles, and opportunities may exist to leverage their complementary aspects to screen more effectively for high emitters.

The Opus AccuScan remote sensing device used in this study applies infrared and ultraviolet light spectrometry to measure exhaust opacity in real-world conditions. The opacity reading is reported relative to CO_2 emissions and is considered a proxy for PM mass emissions. The system can measure thousands of vehicles per day, which makes it particularly convenient for rapid fleet screening of in-use vehicle emissions. The Opus AccuScan RSD is best suited for detecting vehicles with high levels of PM mass emissions, such as diesel vehicles not equipped with a DPF. A former study on heavy-duty vehicle emissions suggested a threshold of 1.5 gPM/kgFuel indicates a tampered DPF with high confidence.[26] However, the Opus system may not be sensitive to instances when the size of particles is too small, in the nanometer range, such as those downstream of a DPF. In some cases, PN emissions might be high due to a partially deteriorated DPF, but mass emissions can remain low.

Tailpipe PN measurement instruments used in advanced PTI programs measure PN concentration using condensation or diffusion charger techniques and can detect particles down to nanometer-scale sizes. Researchers sample the exhaust directly inside the exhaust pipe while the engine idles for about 30 seconds. Only a few hundreds of vehicles can be pulled over and verified per day due to the time requirements for each test. Vehicle owners typically know they will be inspected, which may limit the effectiveness of the inspection.

Figure 30 presents the fuel-specific PM emissions from remote sensing and PN tailpipe concentration for individual vehicles. The results indicate that the correlation between the two techniques is weak but interesting. Vehicles equipped with DPFs can have PN emissions spanning the minimum and maximum range of the instrument (1,000 to 10,000,000 particles per cm^3), but rarely exceed the 1.5 gPM/kgFuel threshold when measured with remote sensing. Euro 3 and 4 vehicles, which are not expected to be equipped with DPFs, have some of the highest PN emissions and may exceed a 1.5 gPM/kgFuel threshold when measured by remote sensing.

During the three days of testing, none of the Euro 5 and newer vehicles tested by both PN measurement instruments and remote sensing had PM emissions that exceeded the 1.5 gPM/kgFuel threshold. In other words, none of these vehicles would have been selected for a deeper inspection with a PN instrument. However, the remote sensing campaign in Brussels offers a much larger sample to evaluate the prevalence of high PM-emitting vehicles. In the entire Brussels remote sensing dataset, PM emission levels for light-duty DPF-equipped vehicles exceeded 1.5 gPM/kgFuel for 2.3% of Euro

25 "Belgium to Adopt PTI-PN Test for DPF Inspections," *DieselNet*, April 7, 2021, https://dieselnet.com/news/2021/04be.php.

26 Mridul Gautam and Donald Stedman, "Correlation of the Real-Time Particulate Matter Emissions Measurements of a ESP Remote Sensing Device (RSD) and a Dekati Electronic Tailpipe Sensor (ETaPS) with Gravimetrically Measured PM from a Total Exhaust Dilution Tunnel System" (California Environmental Protection Agency, March 26, 2010), 61. For a light duty vehicle emitting 130 gCO_2/km or burning 41 gFuel/km, the 1.5 gPM/kgFuel threshold is equivalent to a per-kilometer emission rate of 62 mgPM/km. This value exceeds the 50 mg/km Euro 3 PM emission limit and is an order of magnitude higher than the 5 mg/km Euro 5 PM limit.

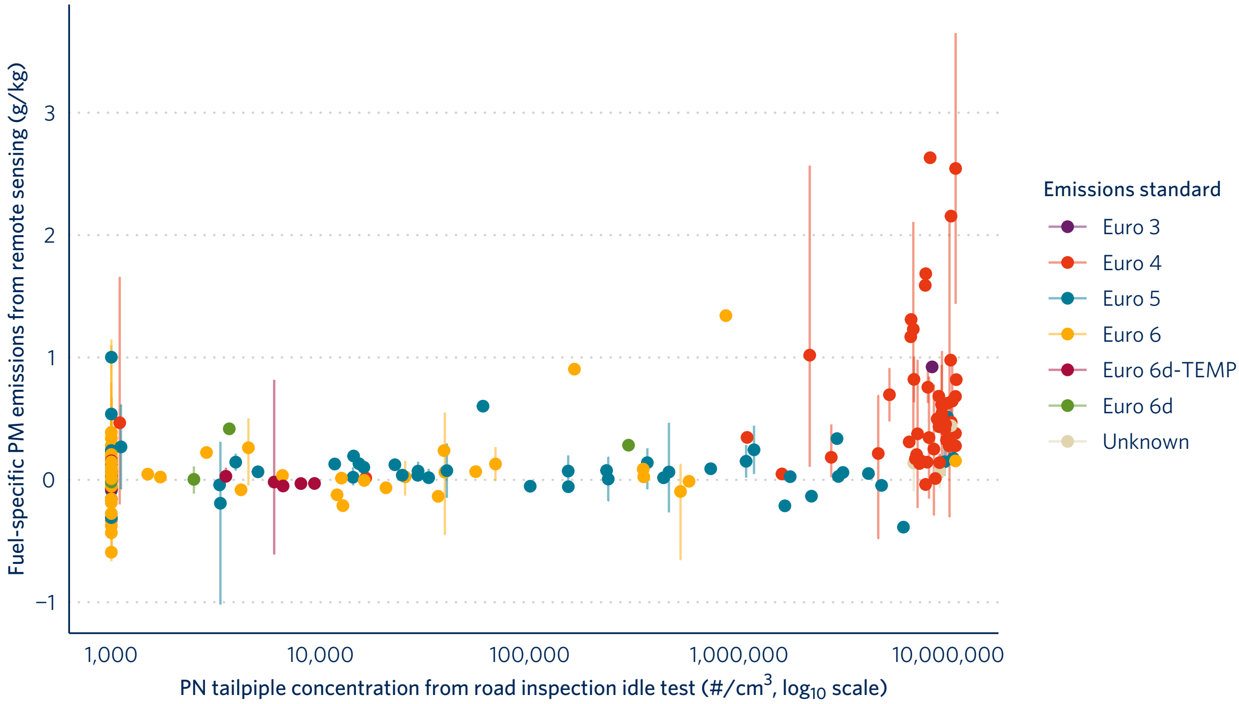


Figure 30. Mean fuel-specific PM emissions for light-duty diesel vehicles from remote sensing compared to PN concentration from road inspection at idle, by emissions standard. The range represents the min-max range when a vehicle was measured more than once with remote sensing.

5 and 1.8% of Euro 6 measurements, which is a level typically observed for non-DPF-equipped vehicles. A wide, non-programmed screening of vehicle PM emissions with remote sensing may identify DPF-faulty vehicles that should be checked with the new PN-counting test at an unanticipated vehicle inspection.

More research is needed to scrutinize the correlation between remote sensing and PN measurement from vehicles with tampered DPFs. However, this first-of-its-kind research suggests that remote sensing may help screen a large fraction of the fleet and identify high-emitting vehicles that need an early PN inspection.

CONCLUSIONS AND POLICY IMPLICATIONS

Motor vehicles are a significant source of air pollutant emissions in Brussels, contributing to the city's air quality challenges and negative health outcomes for its citizens. The TRUE Initiative, as part of its continuing efforts to provide cities with detailed information on the real-world emissions of their vehicle fleets, conducted an extensive vehicle emissions testing study in Brussels in Fall 2020. During the study, researchers made more than 260,000 in-use emissions measurements of 130,588 unique vehicles using remote sensing technology. The testing program also included three days of tailpipe PN testing to provide a more detailed assessment of particle emissions from light-duty vehicles.

We analyzed data collected during the TRUE Brussels study with the goal of providing insights into the real-world effectiveness of some of the key policies and regulations impacting the Brussels fleet and to provide recommendations for their future development. These policies include the LEZ implemented in the Brussels Capital region, the introduction of new stages of European emission standards for new vehicles, and more stringent periodic technical inspection requirements recently introduced by Belgium.

The TRUE Brussels data allow for the assessment of the expected emissions benefits of tightened access restrictions for the Brussels LEZ beginning in January 2022, when Brussels will no longer permit Euro 4 diesel cars and LCVs to enter the city. Euro 4 diesel cars accounted for only 12% of the passenger cars measured during the TRUE study; however, our measurements indicated that they contribute 26% of total passenger car NO_x emissions and 47% of total PM emissions. Similarly, Euro 4 diesels made up 15% of the measured LCV fleet but accounted for more than half of total

PM emissions from this vehicle type. These findings indicate new LEZ requirements will only impact a small percentage of the fleet but will have a disproportionately positive impact on reducing tailpipe emissions, especially PM emissions, from light-duty vehicles operating within the city.

Despite these expected improvements, the next stage of the Brussels LEZ will continue to allow access to the light-duty vehicle groups responsible for the largest share of NO_x emissions—Euro 5 diesels—which we estimate to contribute approximately 40% of total emissions from passenger cars and nearly 50% of emissions from LCVs. Current legislation extends restrictions to these vehicles beginning in 2025. An earlier phase-out would accelerate the NO_x emissions reduction benefits achievable from removing these high-emitting vehicles from the streets of Brussels.

As Brussels tightens the LEZ requirements, RDE-compliant vehicles certified to Euro 6d-TEMP or 6d standards will make up a larger percentage of the Brussels fleet. The TRUE Brussels dataset provides among the first large collections of real-world emissions data for these vehicle groups. We found that the average NO_x emissions of Euro 6d-TEMP and 6d diesel passenger cars are, when expressed on a per kilometer basis, respectively 63% and 74% lower than those from vehicles certified to previous stages of the Euro 6 standard. We also observed similar improvements in the NO_x emissions of RDE-compliant diesel LCVs in the Brussels data. These findings show that the proposed implementation step for the Brussels LEZ banning pre-RDE light-duty vehicles beginning in 2028 is warranted. Because the real-world NO_x emissions of pre-RDE Euro 6 diesel cars and LCVs are significantly greater than other passenger vehicle and LCV groups that will be allowed to access the Brussels LEZ from 2025, earlier action could be considered for these groups, such as banning pre-RDE Euro 6 diesel vehicles in 2025 rather than 2028.

Despite the improved real-world NO_x emissions performance of RDE-compliant diesel vehicles, NO_x levels for these groups remain higher than for their petrol equivalents and exceed laboratory type-approval limits. Furthermore, 17% of Euro 6d-TEMP diesel vehicle families exceeded the on-road type-approval limit, suggesting that the RDE regulation does not sufficiently cover the typical urban conditions of Brussels and providing support for more realistic treatment of urban operations during type-approval testing in the Euro 7 regulation under development.

Most RDE-compliant vehicles measured during the study are likely still within their in-service conformity compliance window, i.e., up to 5 years or 100,000 km, whichever comes first. Questions remain regarding the emission durability of RDE-compliant vehicles and whether emissions performance will be maintained as the vehicles and emission control equipment age beyond the unrealistically short emissions durability period defined in the Euro 6 regulation. We recommend continued monitoring of the real-world emissions of these vehicles as they age, especially as they will be allowed to operate within the Brussels LEZ until 2030 in the case of diesel vehicles and 2035 for petrol vehicles.

Emissions testing result presented here provide further support for actions that address currently unregulated pollutants in the Euro 7 standard. Preliminary evidence from this study indicates an increase in diesel NH_3 emissions for the latest RDE-compliant vehicles, which now approach the levels of petrol vehicles of the same standard. In both cases, the introduction of tailpipe emission limits would help to limit the impacts of these emissions on urban air quality.

Current standards exempt petrol vehicles equipped with indirect injection engines from PM and PN emission limits in place for diesel vehicles and direct injection petrol vehicles. We found that this may lead to higher-than-expected PM emissions from these vehicles. In particular, we identified one Euro 6 petrol LCV model with real-world PM emissions at a level comparable to those of Euro 4 diesel vehicles, which are not equipped with DPFs. As particulate filters continue to reduce the average PM emissions from diesel and direct injection petrol vehicles, indirect injection petrols may become an increasingly large source of traffic-related PM emissions in Brussels.

In addition to tightened standards for new vehicles, continued monitoring is also important to ensure advanced emission control technologies operate effectively throughout vehicle lifetimes. Using a conservative threshold, we found that approximately 2% of the DPF-equipped light-duty diesel vehicles measured in Brussels via remote sensing had PM emissions that indicated some level of failure of the emission control system. These findings are supported by the results of the dedicated tailpipe particle number test program, which registered PN emissions levels well above those expected of vehicles with properly function exhaust aftertreatment systems for 5% of the tested DPF-equipped diesel fleet. As these control technologies grow in prevalence in the fleet, cities face the increasingly important challenge of detecting those vehicles as early as possible and developing mitigation measures to protect the health of their citizens. The recent addition of PN testing requirements to the Belgian PTI program is an important step in addressing this challenge. Further benefits could be realized by tightening high-emitter thresholds and extending requirements to a broader set of vehicles, such as diesel vehicles certified to Euro 5a standards, petrol vehicles, and heavy trucks and buses.

Finally, this study provided insights into the real-world emissions of the taxi, ride-hailing, and bus fleets operating in Brussels. Taxis and ride-hailing vehicles in Brussels are predominantly diesel-powered. These fleets are also, on average, newer than other passenger vehicles in the city due to a 7-year age limit for these high-usage vehicles. Data from this study show that taxis and ride-hailing vehicles emit about 20% more NO_x than the average passenger car, but about 20% less PM. The current age limitation on these vehicles will phase Euro 5 vehicles out of the fleets by the end of 2022, two years ahead of when this would otherwise occur through the planned tightening of LEZ requirements. This phase-out will accelerate NO_x emissions reductions from the taxi and ride-hailing fleets. However, other taxi and ride-hailing groups with elevated real-world NO_x emissions, in particular pre-RDE Euro 6 diesel vehicles, will not be phased out until late 2026. Brussels could consider earlier action to address the real-world emissions of these fleets by, for example, setting Euro 6d LEZ requirements for taxis and ride-hailing vehicles ahead of implementation for the broader passenger vehicle fleet scheduled for 2028, or by requiring all newly registered taxi and ride-hailing vehicles to be zero-emission-capable or, better yet, zero-emission vehicles—a requirement that other European cities have already implemented.

The real-world emissions measurements of buses operating in Brussels show that coach buses certified to Euro VI-D emission standards emit 3 times less NO_x per unit of fuel burnt than buses certified to previous stages of the Euro VI standards. The proposed implementation timeline for the Brussels LEZ requires all buses to meet, at a minimum, Euro VI-D standards beginning in 2028 and be zero-emission by 2036. While these are important steps, the real-world emissions results show that any new buses entering the STIB fleet should be certified to at least Euro VI-D standards. Given the currently available technology and the city's long-term LEZ targets, we further recommend that all transit buses transition to zero-emission alternatives, such as electric options, to be able to deliver the greatest emission reductions across all pollutants.

APPENDIX

The figures and table below show more detailed information on vehicle-specific power and diesel passenger car emissions (Figure A1), carbon monoxide emissions (Figures A2 and A3), and NO_x emissions from Euro 6d-TEMP passenger cars (Table A1).

EFFECT OF VEHICLE SPECIFIC POWER ON DIESEL PASSENGER CAR FUEL-SPECIFIC EMISSIONS

Below, the difference in vehicle dynamics conditions is investigated for diesel vehicles. Figure A1 illustrates the differences in NO_x emissions from diesel passenger cars between Brussels and TRUE. The figure explores the relationship between VSP and NO_x emissions by emissions standard using generalized additive models, as implemented in the mgcv19 and ggplot220 packages for the R software environment. VSP ranges are truncated from the 5th to 95th percentile per group to avoid plotting relationships for ranges with scarce data.

These results confirm that for Euro 3 and Euro 4 vehicles, Brussels NO_x measurements are higher than TRUE levels, which VSP alone cannot explain. For Euro 6 predating the RDE regime, Brussels NO_x emissions are lower than TRUE levels.

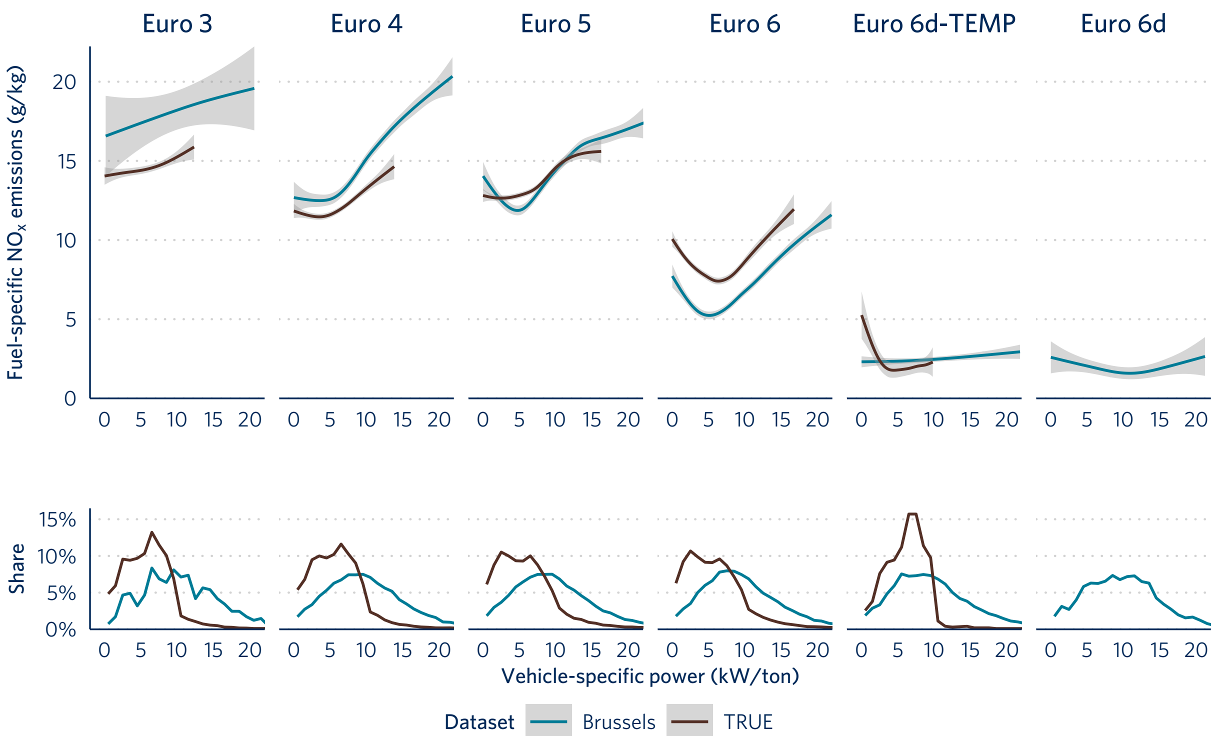


Figure A1. Top graph: Comparison of fuel-specific NO_x emissions from Euro 3 through Euro 6d-TEMP diesel passenger cars as a function of vehicle specific power in multiple remote sensing datasets. The relationship between NO_x emissions and vehicle specific power is represented using generalized additive models with 95% confidence intervals. Bottom graph: Share of measurements in each dataset per vehicle specific power bin. Bin width: 2 kW/ton.

PASSENGER CAR CARBON MONOXIDE EMISSIONS

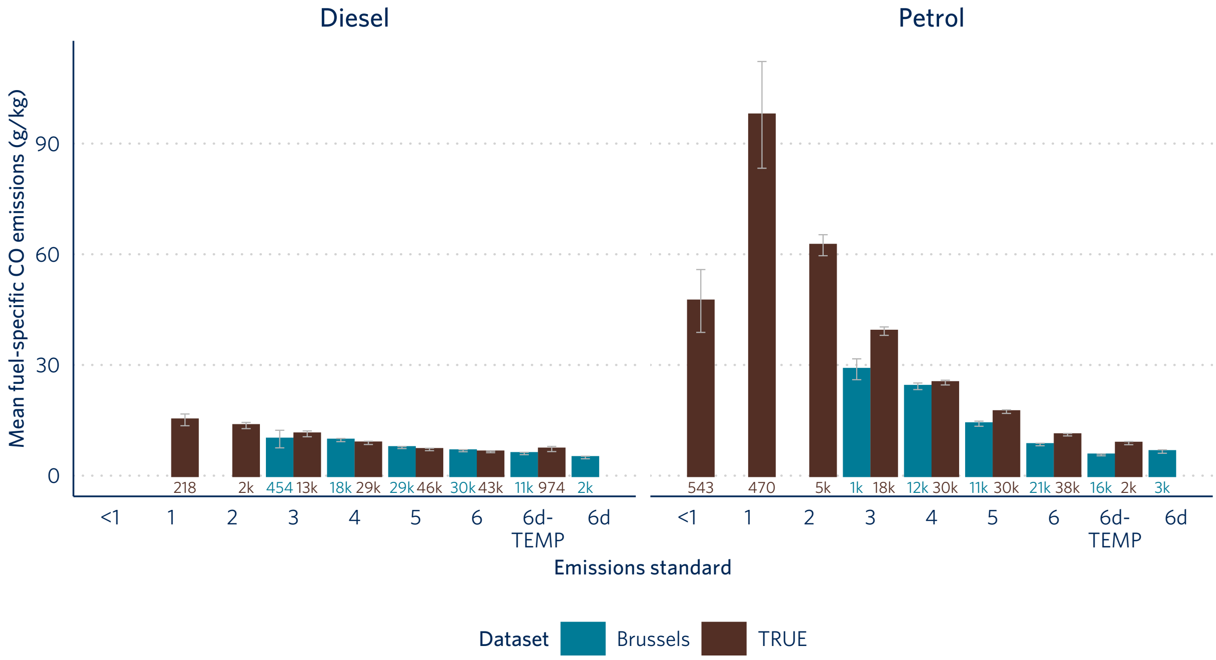


Figure A2. Mean fuel-specific carbon monoxide (CO) emissions from diesel and petrol passenger cars by emissions standard for Brussels and TRUE remote sensing data. The number of measurements is presented below each bar. Whiskers represent the 95% confidence interval of the mean. Only results for groups with at least 100 measurements.

LIGHT COMMERCIAL CARBON MONOXIDE EMISSIONS

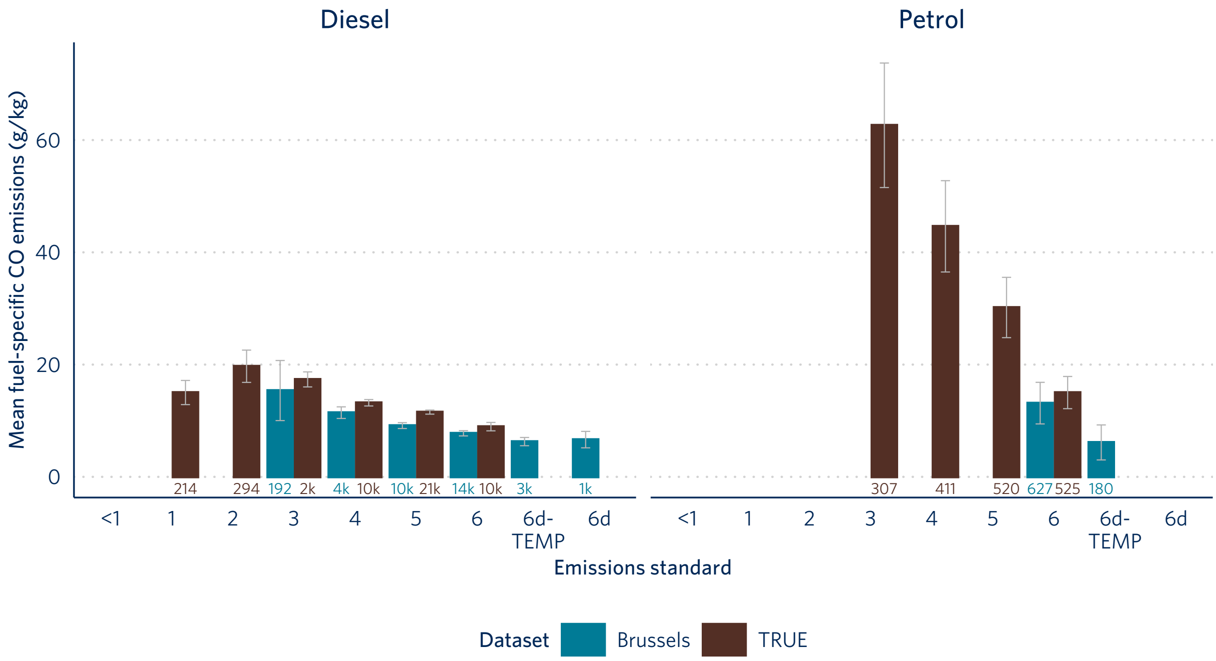


Figure A3. Mean fuel-specific carbon monoxide emissions from diesel and petrol light commercial vehicles by emissions standard for Brussels and TRUE remote sensing data. The number of measurements is presented below each bar. Whiskers represent the 95% confidence interval of the mean. Only results for groups with at least 100 measurements are shown.

Euro 6d-TEMP passenger car families nitrogen oxide emissions

Table A1. Vehicle families type-approved to the Euro 6d-TEMP standard.

Fuel type	Manufacturer group	Engine displacement bins (cc)	Number of measurements	Average NO_x emissions (g/km)	95% confidence interval (g/km)
Petrol	Toyota	1490–1510	51	-0.015	−0.046-0.017
Petrol	Mazda	2470–2490	32	0.002	−0.02-0.024
Petrol	Volvo	1950–1970	228	0.013	−0.019-0.045
Petrol	Ford	1070–1090	82	0.016	−0.033-0.065
Petrol	Mazda	1990–2010	146	0.021	−0.014-0.055
Petrol	Daimler	2990–3010	34	0.027	−0.054-0.108
Petrol	Volvo	1490–1510	36	0.028	−0.049-0.106
Petrol	BMW	1490–1510	1227	0.033	0.02-0.045
Petrol	Toyota	990–1010	30	0.035	−0.014-0.084
Petrol	BMW	1990–2010	447	0.042	0.023-0.061
Petrol	Daimler	1590–1610	251	0.047	0.009-0.085
Petrol	Suzuki	1230–1250	112	0.048	0.014-0.082
Petrol	Ford	990–1010	528	0.050	0.029-0.071
Petrol	Honda	1490–1510	82	0.052	0.023-0.08
Petrol	Hyundai Motor Company	1350–1370	248	0.054	0.031-0.078
Petrol	Hyundai Motor Company	990–1010	320	0.060	0.03-0.09
Petrol	Toyota	1970–1990	31	0.062	−0.024-0.149
Diesel	FCA	2130–2150	57	0.066	−0.036-0.168
Petrol	VW Group	1390–1410	107	0.067	0.009-0.125
Petrol	VW Group	1970–1990	249	0.068	0.031-0.104
Petrol	Renault-Nissan	990–1010	560	0.069	0.047-0.091
Petrol	Mazda	1490–1510	66	0.071	0.027-0.116
Diesel	PSA	1990–2010	148	0.074	0.041-0.106
Petrol	Volvo	1470–1490	160	0.075	0.03-0.121
Petrol	Ford	1490–1510	97	0.075	0.032-0.118
Petrol	PSA	1590–1610	107	0.081	0.022-0.139
Petrol	FCA	1350–1370	410	0.082	0.048-0.116
Diesel	Daimler	2910–2930	34	0.082	−0.044-0.208
Petrol	FCA	1990–2010	41	0.085	−0.05-0.22
Petrol	Daimler	1330–1350	266	0.086	0.042-0.13
Petrol	PSA	1390–1410	158	0.088	0.052-0.124

Fuel type	Manufacturer group	Engine displacement bins (cc)	Number of measurements	Average NO_x emissions (g/km)	95% confidence interval (g/km)
Petrol	FCA	1330–1350	100	0.089	0.043–0.134
Petrol	VW Group	2990–3010	59	0.091	−0.012–0.194
Petrol	Suzuki	1370–1390	97	0.091	0.029–0.154
Petrol	Toyota	1190–1210	67	0.092	0.031–0.152
Diesel	Toyota	1990–2010	35	0.093	0.024–0.161
Diesel	Renault-Nissan	1450–1470	566	0.094	0.072–0.116
Petrol	VW Group	1490–1510	1630	0.094	0.078–0.11
Petrol	Hyundai Motor Company	1590–1610	462	0.095	0.063–0.128
Petrol	Daimler	3970–3990	38	0.097	0.004–0.19
Petrol	PSA	1350–1370	79	0.098	0.004–0.191
Petrol	VW Group	990–1010	2466	0.098	0.086–0.111
Petrol	Renault-Nissan	1330–1350	923	0.099	0.078–0.12
Petrol	Jaguar Land Rover	1990–2010	126	0.102	0.04–0.164
Diesel	Daimler	1450–1470	919	0.103	0.085–0.121
Diesel	Daimler	1930–1950	474	0.103	0.071–0.136
Petrol	FCA	1230–1250	324	0.103	0.071–0.136
Petrol	PSA	1190–1210	1190	0.106	0.087–0.125
Diesel	BMW	1490–1510	218	0.111	0.076–0.146
Diesel	BMW	1990–2010	844	0.111	0.092–0.13
Petrol	Renault-Nissan	1590–1610	63	0.111	0.037–0.186
Petrol	Mitsubishi	1490–1510	33	0.112	0.012–0.211
Petrol	Daimler	1990–2010	158	0.112	0.06–0.163
Diesel	BMW	2990–3010	144	0.113	0.052–0.173
Diesel	Jaguar Land Rover	1990–2010	203	0.114	0.069–0.159
Diesel	FCA	1590–1610	150	0.115	0.048–0.183
Petrol	Suzuki	990–1010	77	0.116	0.046–0.186
Petrol	PSA	990–1010	114	0.116	0.05–0.183
Diesel	Jaguar Land Rover	2990–3010	46	0.120	0.008–0.231
Diesel	VW Group	1950–1970	1264	0.121	0.102–0.14
Petrol	FCA	990–1010	233	0.123	0.074–0.171
Diesel	Daimler	1590–1610	291	0.124	0.086–0.161
Petrol	BMW	2990–3010	81	0.126	0.028–0.225
Petrol	PSA	1210–1230	73	0.127	0.042–0.212

Fuel type	Manufacturer group	Engine displacement bins (cc)	Number of measurements	Average NO_x emissions (g/km)	95% confidence interval (g/km)
Petrol	Hyundai Motor Company	1230–1250	195	0.129	0.083–0.175
Diesel	Renault-Nissan	1990–2010	56	0.134	0.039–0.23
Diesel	PSA	1590–1610	127	0.135	0.071–0.199
Diesel	PSA	1490–1510	1538	0.145	0.129–0.161
Diesel	Volvo	1950–1970	931	0.149	0.126–0.171
Petrol	Renault-Nissan	890–910	178	0.163	0.107–0.219
Diesel	Ford	1990–2010	159	0.165	0.093–0.238
Diesel	Renault-Nissan	1730–1750	145	0.175	0.117–0.233
Diesel	VW Group	1590–1610	1228	0.181	0.153–0.209
Diesel	Hyundai Motor Company	1590–1610	276	0.188	0.145–0.23
Diesel	Ford	1490–1510	215	0.205	0.151–0.259

Note. Only results with 30 or more measurements are shown. In a few cases, the lower bound of the confidence interval or the average emissions may be negative. This can occur for two reasons. First, negative lower bounds can be artifacts of reporting two-sided confidence intervals based on the Student's t-distribution and can occur in subsamples with low means, high variance, and/or few observations. Second, it is possible to have individual negative emissions readings when the pollutant level in the exhaust's plume is lower than the ambient air level.

TRUE—The Real Urban Emissions Initiative
FIA Foundation, 60 Trafalgar Square, London WC2N 5DS, United Kingdom
For more information contact: **true@fiafoundation.org**
@TRUE_Emissions
www.trueinitiative.org