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Remote sensing of motor vehicle emissions in Krakow

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ICCT CONSULTING REPORT

ACKNOWLEDGMENTS

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INTRODUCTION

Airborne particulate matter ($PM_{2.5}$), ozone (O_3), and nitrogen dioxide (NO_2) exposure was responsible for over 45,000 premature deaths in Poland in 2016,[1] and people in Poland are more likely to die from air pollution than the average European Union (EU) resident.[2] The problem is particularly prevalent in Polish cities, which regularly breach EU air quality limits. Of the 50 cities in the European Union (EU) with the highest rates of air pollution, 36 are in Poland.[3]

On-road transportation in Poland is the second largest source of air pollution and the single largest source of nitrogen oxides (NO_x). Among other contributing factors, like many countries in the EU, Poland has a high share of diesel-fueled vehicles known to exceed the NO_x emission laboratory certification limits during real-world driving. Moreover, Poland has one of the oldest vehicle fleets in the EU, with an average passenger car age of 14 years in 2018 compared to the EU average of 11 years.[4] Older vehicles were designed to less stringent emission limits than their modern counterparts and are more likely to suffer from deterioration of emission control systems.

To address air pollution from on-road transport, Poland adopted the Electric Mobility and Alternative Fuel Law in January 2018. The law includes measures to stimulate the electric vehicle market, such as permitting cities to create "clean transport zones." Based on this regulation, the City of Krakow put in place the first pilot clean transport zone in the country. It was implemented for nine months beginning in January 2019. Access to the zone was restricted to battery-electric, fuel-cell, and compressed gas vehicles, but it granted exceptions to residents. The City of Krakow is currently considering new policies to reduce vehicle emissions, including establishing a new low-emission zone.

This study fits into a broader plan of the City of Krakow to tackle traffic-related emissions and identify the most significant contributors. City authorities commissioned a testing campaign in June 2019 to better understand the actual impact of motor vehicle emissions on air quality. Remote sensing instruments were used to measure the real-world NO_x, carbon monoxide, and particulate matter emissions of approximately 100,000 vehicles. Measurements were made via spectroscopy, which can measure emissions remotely as vehicles drive by the equipment. This nonintrusive method of measuring real-world emissions can capture a snapshot of the exhaust plume from thousands of vehicles in a single day, thus making it particularly effective at monitoring a large fraction of the vehicle fleet. Once collated, the results can provide an accurate picture of a given group of vehicles over a range of operating conditions.

The City of Krakow commissioned this report to provide an analysis of the real-world emissions data of its vehicle fleet. The paper provides an overview of the vehicle fleet composition in Krakow and compares the remote sensing emission measurements in Krakow against measurements made in other European cities over the past decade from the CONOX[5] database and measurements collected by The Real Urban Emissions

1 European Environment Agency, "Air Quality in Europe 2019," EEA Report No 10/2019, (October 2019), https://www.eea.europa.eu/publications/air-quality-in-europe-2019.

2 European Environment Agency, "Poland - Air Pollution Country Fact Sheet 2019," accessed June 17, 2020, https://www.eea.europa.eu/themes/air/country-fact-sheets/2019-country-fact-sheets/poland.

3 World Bank Group, "Air Quality in Poland, What Are the Issues and What Can Be Done?" Policy research working paper 144191, (2019), http://documents1.worldbank.org/curated/en/426051575639438457/pdf/Air-Quality-in-Poland-What-are-the-Issues-and-What-can-be-Done.pdf.

4 ACEA, "ACEA Report: Vehicles in Use – Europe 2019," (2019), https://www.acea.be/uploads/publications/ACEA_Report_Vehicles_in_use-Europe_2019.pdf.

5 In 2016, the Bundesamt für Umwelt (Switzerland's Federal Office for the Environment) funded the CONOX project to pool European remote sensing data. Data from individual remote sensing campaigns between 2011 and 2017 in France, Spain, Sweden, Switzerland, and the United Kingdom were gathered and harmonized in one database.

Initiative in London[6] and Paris[7]. In particular, the difference in NO_x emissions from diesel passenger cars between data sources is examined by emission standard as a function of the vehicle's dynamic conditions and ambient temperature. Additional analyses in this report investigates the share of total NO_x emissions in Krakow from passenger cars by vehicle emission standard and fuel type. Two case studies examine emissions from Krakow's taxis and bus fleet and scrutinize particulate matter emissions from diesel passenger cars, focusing on evidence of tampered or malfunctioning particulate filters. The study concludes with policy suggestions and recommendations for research.

6 Tim Dallmann, Yoann Bernard, Uwe Tietge, and Rachel Muncrief, *Remote Sensing of Motor Vehicle Emissions in London*, (ICCT: Washington, D.C., 2018), https://theicct.org/publications/true-london-dec2018.

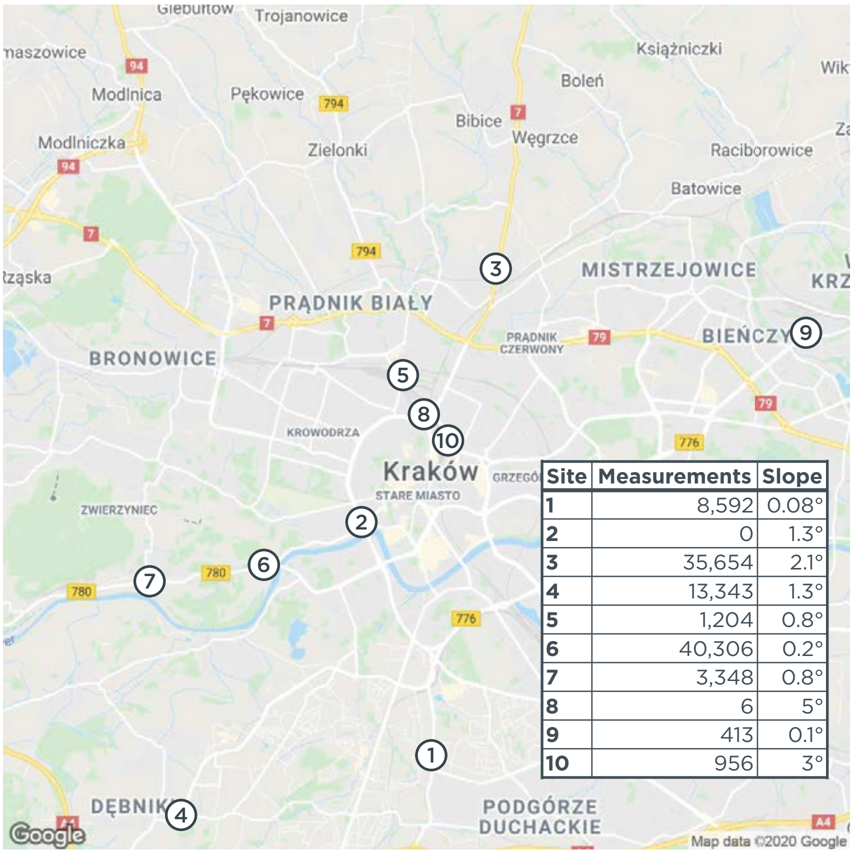
7 Tim Dallmann, Yoann Bernard, Uwe Tietge, and Rachel Muncrief, *Remote Sensing of Motor Vehicle Emissions in Paris*, (ICCT: Washington, D.C., 2019), https://theicct.org/publications/on-road-emissions-paris-201909.

METHODOLOGY

DATA SOURCES

Remote sensing is a non-invasive method of measuring emissions of vehicles during real-world, on-road operation.[8] Snapshots of the exhaust plume content and driving conditions, including vehicle speed and acceleration, are collected from passing vehicles at sampling sites. Ambient conditions such as temperature are also recorded, and pictures of the license plate are taken to retrieve technical vehicle characteristics from vehicle registries.[9]

Remote sensing measurements were collected over 17 days from June 10 to July 1, 2019. In total, 103,827 measurements were collected using the Opus RSD5000 remote sensing instrument. Details on the campaign are provided in an English-language report by Opus RSE[10] and a Polish summary is available from the Krakow Public Transport Authority.[11] Figure 1 displays the location of the ten sampling sites and the number of measurements collected at each site.



Site	Measurements	Slope
1	8,592	0.08°
2	0	1.3°
3	35,654	2.1°
4	13,343	1.3°
5	1,204	0.8°
6	40,306	0.2°
7	3,348	0.8°
8	6	5°
9	413	0.1°
10	956	3°

Figure 1. Map of remote sensing measurement sites in Krakow.

8 Jens Borken-Kleefeld and Tim Dallmann, *Remote Sensing of Motor Vehicle Exhaust Emissions*, (ICCT: Washington, D.C., 2018), https://theicct.org/publications/vehicle-emission-remote-sensing.

9 In European remote sensing campaigns, license plate numbers are deleted from the data as soon this process is completed. Information on vehicle owners or drivers is not retrieved, and any data that could be considered personally identifiable information is anonymized in accordance with the General Data Protection Regulation.

10 Opus RSE, "Characterization of Real-World Motor Vehicle Emissions in Krakow" (May 2020), https://www.opusrse.com/projects/public-administrations-1/krakow/.

11 "Innowacyjne Badania Spalin w Krakowie," accessed June 10, 2020, http://mobilnykrakow.pl/wp-content/uploads/2019/12/Badania-spalin-Krakow_final.pdf.

For this analysis, the Krakow measurements are compared with European remote sensing measurements from the CONOX database. The database, funded by Switzerland's Federal Office for the Environment, includes data collected in France, Spain, Sweden, Switzerland, and the United Kingdom.[12] We augmented the latest database with data from a remote sensing campaign in Paris conducted in mid-2018.[13] Note that, throughout the report, blue graph elements are used for Krakow and brown are used for CONOX remote sensing data. All whiskers and shaded areas in graphs refer to 95% confidence intervals of the mean.

DATA PREPARATION

The methods for analyzing and aggregating remote sensing measurements used in this report have been documented in previous studies.[14] The conversion of tailpipe pollutant concentration ratios to distance-specific estimates in gram per kilometer (g/km), the unit used in European light-duty vehicle regulations, is performed by combining the average pollutant emissions across multiple remote-sensing records with vehicle type-approval CO_2 emission values and data on real-world fuel-consumption.[15] The engine load, is estimated using vehicle specific power (VSP), conventionally reported in kilowatt per ton (kW/ton), which relies on vehicle speed and acceleration, road grade, and the average values of aerodynamic and rolling resistance of vehicles to estimate instantaneous power demand.

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 Krakow data, information on the emissions standard was available for only 14% of vehicles which were primarily newer vehicles type-approved to Euro 6 and Euro 6d-TEMP. Because the emissions standard is an essential variable for analyzing vehicle emissions, a methodology was developed to estimate emission standards based on the registration date of the vehicle. European regulations phase in emission standards by first only applying new emission limits to new type approvals and later applying them to all new vehicle registrations. The phase-in period typically lasts one year. In order to provide conservative estimates for comparisons involving Krakow data, the emission standard being phased out was assigned to vehicles registered during a phase-in period. To illustrate the uncertainty involved in estimating emission standards, Figure 2 presents

12 Jens Borken-Kleefeld, Stefan Hausberger, Peter McClintock, James Tate, David Carslaw, Yoann Bernard, and Åke Sjödin, "Comparing Emission Rates Derived from Remote Sensing with PEMS and Chassis Dynamometer Tests—CONOX Task 1 Report" (Federal Office for the Environment, Switzerland, May 2018), https://www.ivl.se/download/18.2aa26978160972788071cd7b/1529408235244/comparing-emission-rates-derived-from-remote-sensing-with-pems-and-chassis-dynamometer-tests-conox-task1-report.pdf; Å Sjödin et al., "Real-Driving Emissions from Diesel Passenger Cars Measured by Remote Sensing and as Compared with PEMS and Chassis Dynamometer Measurements—CONOX Task 2 Report" (Federal Office for the Environment, Switzerland, May 2018), https://www.ivl.se/download/18.2aa26978160972788071cd79/1529407789751/real-driving-emissions-from-diesel-passengers-cars-measured-by-remote-sensing-and-as-compared-with-pems-and-chassis-dynamometer-measurements-conox-task-2-r.pdf; Jens Borken-Kleefeld, Stefan Hausberger, Peter McClintock, James Tate, David Carslaw, Yoann Bernard, Åke Sjödin1, "Contribution of Vehicle Remote Sensing to In-Service/Real Driving Emissions Monitoring—CONOX Task 3 Report" (Federal Office for the Environment, Switzerland, May 2018), https://www.ivl.se/download/18.2aa26978160972788071cd7b/1529408235244/comparing-emission-rates-derived-from-remote-sensing-with-pems-and-chassis-dynamometer-tests-conox-task1-report.pdf.

13 Dallmann et al., *Remote Sensing of Motor Vehicle Emissions in Paris*.

14 Yoann Bernard, Uwe Tietge, John German, and Rachel Muncrief, *Determination of Real-World Emissions from Passenger Vehicles Using Remote Sensing Data*, (TRUE Initiative: Washington, D.C., 2018), https://theicct.org/publications/real-world-emissions-using-remote-sensing-data; Uwe Tietge, Yoann Bernard, John German, and Rachel Muncrief, *A Comparison of Light-Duty Vehicle NOx 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.

15 Vehicles CO2 type approval information are assumed to be based on the new WLTP for Euro6d-TEMP vehicles, and on the NEDC for other euro standards. The gap between type-approval and real-world CO_2 is addressed in: Jan Dornoff, Uwe Tietge, Peter Mock, *On the way to "real-world" CO2 values: The European passenger car market in its first year after introducing the WLTP,* (ICCT: Washington, D.C., 2020), https://theicct.org/publications/way-real-world-co2-values-european-passenger-car-market-its-first-year-after

the share of passenger cars by emissions standard for which the value was reported, estimated outside the phase-in period, or estimated during a phase-in period. The reported standard was used to determine Euro 6d-TEMP vehicles as the phase-in period ended in September 2019, after the Krakow remote sensing campaign was completed.

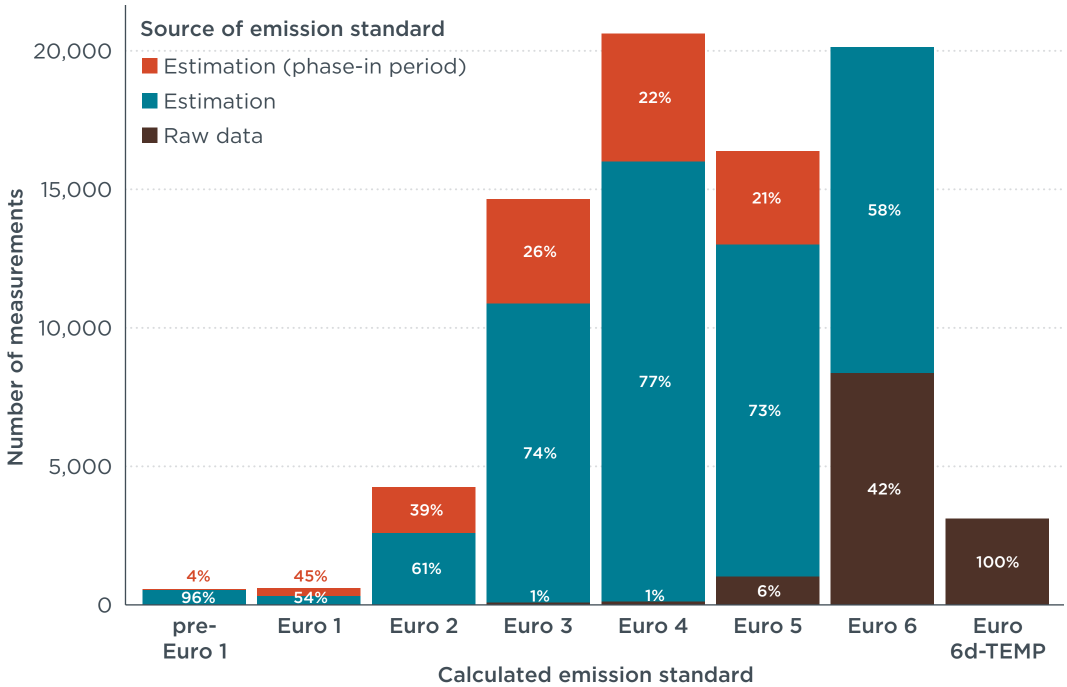


Figure 2. Source of emissions standard values for passenger cars.

SAMPLE OVERVIEW

Figure 3 provides an overview of the Krakow samples by vehicle category, fuel type, and emissions standard. The majority (77%) of measurements pertained to passenger cars, with light commercial vehicles (8%), and buses (1%) accounting for most of the remaining identifiable vehicles. The vehicle category could not be identified for 11% of measurements. The majority (54%) of passenger cars were petrol vehicles, while the vast majority (83%) of light commercial vehicles were diesel vehicles. Less than 1% of passenger cars measured in Krakow predated European emission standards, and approximately 4% of passenger cars were type-approved to the current emission standard, Euro 6d-TEMP. Compared with the most recent campaign in the CONOX database, the 2018 Paris campaign, the share of older vehicles is substantially higher in the Krakow measurements as evidenced by the fact that Euro 4 was the most common emission standard in Krakow while Euro 6 was the most common emission standard in Paris. As a result, Krakow measurements are a key data source for both older and modern vehicles.

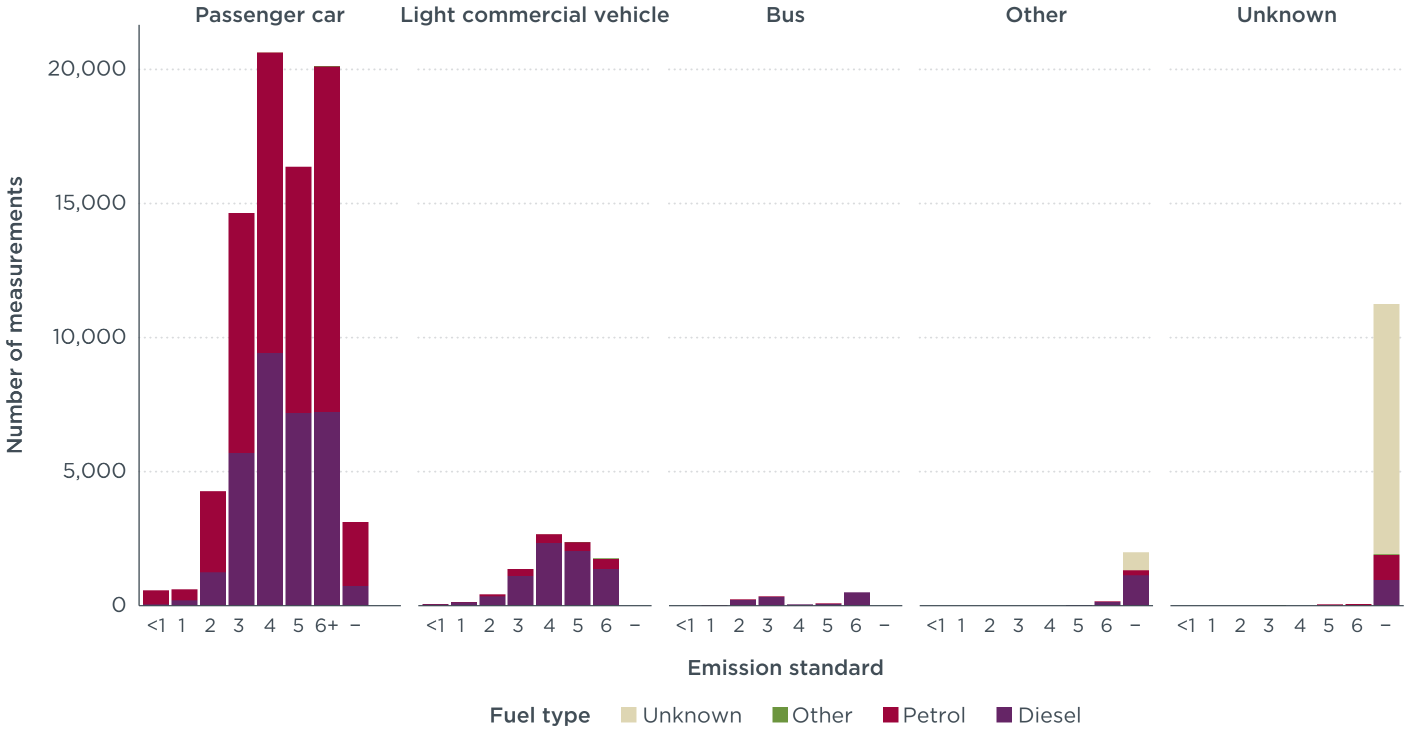


Figure 3. Number of remote sensing measurements by vehicle category, estimated emissions standard, and fuel type. Euro <1 refers to vehicle predating Euro standards; 6+ refers to the Euro 6 and 6d-TEMP emission standard; dashes (-) represent unknown values.

Table 1 provides an overview of vehicle characteristics and measurement conditions in the Krakow and CONOX data. Vehicles measured in Krakow were, on average, two years older than vehicles in the CONOX database. This effect is more pronounced for early emission standards, for which vehicles in Krakow were up to 11 years older than the CONOX average. Median type-approval CO_2 emissions were consistently lower in Krakow for vehicles type-approved to the Euro standards 3–4, and consistently higher than CONOX median values since Euro 5. Measurements in Krakow were conducted during a heat wave, with median ambient temperatures near 30°C, exceeding the median temperature during the Paris 2018 measurement campaign by almost 4°C and making Krakow the hottest remote sensing campaign in the CONOX database. The estimated vehicle-specific power (VSP) values ranged from 2 to 10 kW/ton, and the median value of approximately 7 kW/ton was considerably lower than median engine load in the CONOX database, particularly when compared with the high-load conditions in the Zurich measurements.[16] This pattern is reflected in the average speed below 40 km/h and average acceleration below 2 km/h/s in Krakow, both of which are consistently lower than CONOX averages.

16 Tietge et al., *A Comparison of Light-Duty Vehicle NOx Emissions Measured by Remote Sensing in Zurich and Europe*.

Table 1: Summary of remote sensing testing conditions and passenger car fleet characteristics in Krakow (blue) and the CONOX database (brown). In this table, the Euro 6 group includes Euro 6d-TEMP vehicles.

	Measurements	Avg. vehicle age (years)	Avg. road grade	Certified CO_2 emissions (g/km,EDC)	Ambient temperature (°C)	Vehicle-specific power (kW/ton)	Acceleration (km/h/s) over speed (km/h)
pre-Euro 2 Diesel	258 681	25 19	2.4% 5.0%	218	21.6 28.9	7 9.2	
pre-Euro 2 Petrol	907 5,979	33 22	2.2% 7.7%	137 194	21.8 29.9	6.8 14.6	
Euro 2 Diesel	1,246 5,076	20 17	2.2% 3.6%	163	22.2 29.6	6.9 8.1	
Euro 2 Petrol	3,009 20,828	20 16	2.0% 6.0%	183 232	21.5 29.4	6.8 12.3	
Euro 3 Diesel	5,705 33,564	16 12	2.1% 3.4%	147 159	22 29.9	6.8 7.5	
Euro 3 Petrol	8,928 43,923	16 12	2.0% 4.5%	156 172	19.7 29.7	6.8 9.3	
Euro 4 Diesel	9,416 77,876	11 7	2.0% 3.7%	145 154	21.7 29.6	6.8 7.9	
Euro 4 Petrol	11,212 103,094	11 9	2.0% 5.7%	153 163	20.6 29.9	6.8 12.2	
Euro 5 Diesel	7,191 113,084	6 4	1.9% 4.1%	130 139	21.9 29.9	6.8 8.3	
Euro 5 Petrol	9,176 84,374	6 4	1.9% 5.8%	134 139	20.7 30	6.8 12.1	
Euro 6 Diesel	7,981 64,546	2 1	1.8% 2.9%	114 130	23 29.8	6.2 6.8	
Euro 6 Petrol	15,251 40,691	2 2	1.9% 3.7%	118 132	22.3 29.8	6.9 7.9	
Total	80,280 593,716	9 7	2.0% 4.5%	139 139	21.6 29.8	6.8 9.2	

The 2019 Krakow remote sensing campaign measurements stands out from the CONOX database for three reasons. First, the Krakow measurements form the first campaign conducted in Poland, with other campaigns focusing on France, Spain, Sweden, Switzerland, and the United Kingdom. Second, the average vehicle age was considerably higher in Krakow than in other remote sensing campaigns. Somewhat counterintuitively, as the most recent campaign, the Krakow measurements are also the largest source of data for Euro 6d-TEMP vehicles compared to historical data in the CONOX database. Third, measurement conditions were exceptional, with lower-than-average estimated engine load and the warmest weather conditions among all campaigns.

ANALYSIS AND RESULTS

LIGHT-DUTY VEHICLE NITROGEN OXIDES EMISSIONS

Vehicles emit nitrogen oxides in the form of nitrogen monoxide (NO) and nitrogen dioxide (NO_2) during operation. Both pollutants were measured in this campaign. NO is not considered dangerous to humans at typical ambient conditions, but it turns into harmful NO_2 within a few hours of contact with oxygen in the surrounding air. Therefore, this analysis follows the common practice of reporting vehicle emission in mass of NO_x, the sum of NO_2 and NO mass emissions, with the latter expressed in NO_2-equivalents to account for its eventual conversion to NO_2.

Figure 4 shows the average fuel-specific NO_x emissions in grams of NO_x emitted per kilogram of fuel burned (g/kg) from passenger cars by fuel type and emissions standard, and compares the levels found in the Krakow and CONOX data. While NO_x emissions from petrol passenger cars decreased with increasingly stringent emission standards, emissions from diesel passenger cars only substantially decreased with the introduction of Euro 6 and Euro 6d-TEMP. Comparing the Krakow and CONOX results, NO_x emissions from diesel passenger cars were consistently lower in Krakow than in CONOX, with the difference ranging from 17% to 37%. The opposite was true for petrol vehicles, with NO_x emissions in the Krakow data typically exceeding CONOX levels, with the difference being more pronounced for early emission standards. The difference between the Krakow and CONOX petrol emissions is likely due to deterioration effects: NO_x emissions of petrol passenger cars have been shown to increase with vehicle mileage and petrol vehicles of early emission standards were significantly older in Krakow than in the CONOX database (see Table 1).[17]

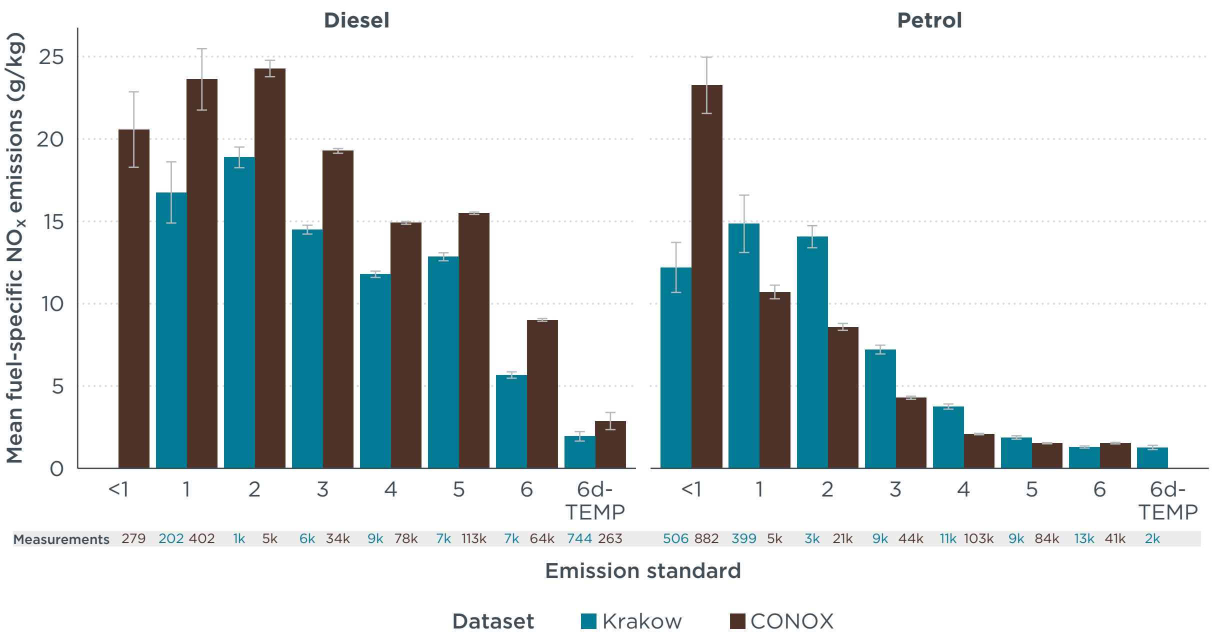


Figure 4. Mean fuel-specific NO_x emissions from diesel and petrol passenger cars, grouped by emission standard, for Krakow and CONOX remote sensing data. The number of measurements is presented below each bar. Whiskers represent the 95% confidence interval of the mean. Results are only shown for groups with at least 100 measurements.

17 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.

Figure 5 illustrates the differences in NO_x emissions from diesel passenger cars between Krakow and CONOX. Both VSP and ambient temperature have been shown to impact NO_x emissions from diesel passenger cars.[18] The figure explores the relation between VSP and NO_x emissions by emission standard using generalized additive models, as implemented in the *mgcv*[19] and *ggplot2*[20] packages for the R software environment.[21] VSP ranges are truncated, from the 5th to 95th percentile per group, to avoid plotting relationships for ranges with scarce data. The figure also differentiates between ambient temperature ranges in the CONOX data, where brown lines represent the full temperature range and orange lines represent CONOX data filtered by the ambient temperature range in Krakow measurements.

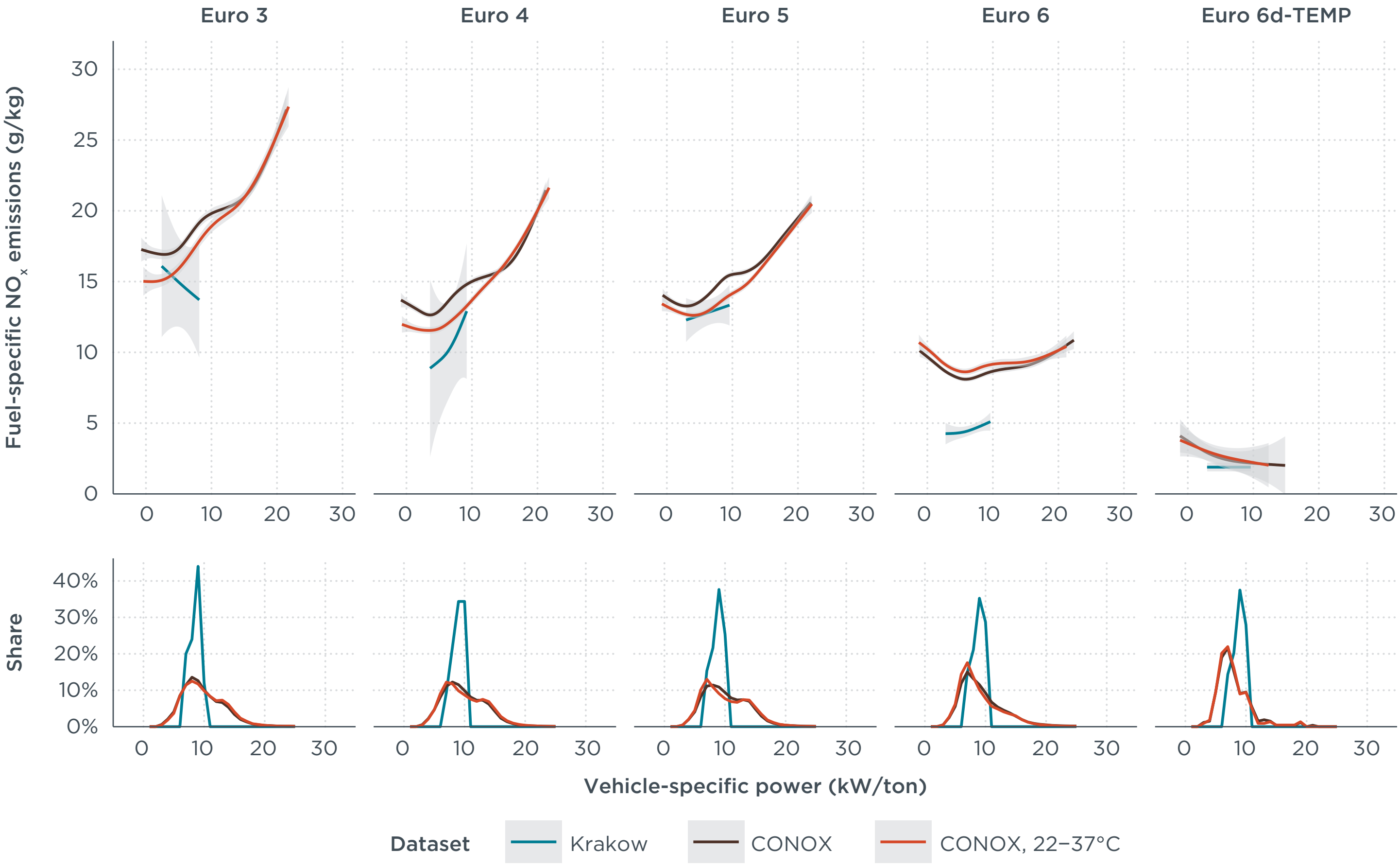


Figure 5. Top graph: Comparison of fuel-specific NO_x emissions from Euro 3 through Euro 6d-TEMP diesel passenger cars as a function of VSP in multiple remote sensing datasets: Krakow (blue), CONOX (brown), and CONOX filtered for Krakow ambient temperature range (orange). The relationship between NO_x emissions and VSP is represented using generalized additive models with 95% confidence intervals. Bottom graph: Share of measurements in each dataset per VSP bin (bin width: 2 kW/ton).

18 Stuart Kenneth Grange et al., "Strong Temperature Dependence for Light-Duty Diesel Vehicle NO_x Emissions," *Environmental Science & Technology*, May 16, 2019, acs.est.9b01024, https://doi.org/10.1021/acs.est.9b01024; Borken-Kleefeld et al., "Comparing Emission Rates Derived from Remote Sensing with PEMS and Chassis Dynamometer Tests—CONOX Task 1 Report"; Dallmann et al., *Remote Sensing of Motor Vehicle Emissions in Paris*; Tietge et al., *A Comparison of Light-Duty Vehicle NOx Emissions Measured by Remote Sensing in Zurich and Europe*; David C. Carslaw et al., "The Importance of High Vehicle Power for Passenger Car Emissions," *Atmospheric Environment* 68 (April 2013): 8–16, https://doi.org/10.1016/j.atmosenv.2012.11.033.

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

20 Hadley Wickham, *Ggplot2: Elegant Graphics for Data Analysis - Rev 2016*, Use R! (Cham: Springer International Publishing, 2016), https://doi.org/10.1007/978-3-319-24277-4.

21 R Core Team, "R: A Language and Environment for Statistical Computing" (R Foundation for Statistical Computing, 2020), http://www.R-project.org/.

Figure 5 indicates that NO_x measurements at comparatively low power demand in Krakow generally align with NO_x levels in the CONOX database at similar VSP ranges. Filtering for similar ambient temperature ranges in CONOX data further reduces NO_x emissions levels for Euro 3–5 and closer aligns the Krakow and CONOX averages. Euro 6 vehicles are a notable exception: neither VSP nor ambient temperature account for the differences between Krakow and CONOX measurements. We posit that the Krakow measurements include Euro 6d-TEMP vehicles that were reported to be Euro 6 vehicles—more than 80% of Euro 6 diesel passenger cars sampled in Krakow were registered after the phase-in of Euro 6d-TEMP began in September 2017—thus artificially reducing the average NO_x emissions of the Euro 6 group.

Figure 6 presents average distance-specific NO_x emissions by fuel type and emissions standard in Krakow and CONOX data. Overall, trends in emission levels and differences between the Krakow and CONOX results are similar to what is shown in Figure 4. NO_x emissions from petrol vehicles decreased with increasingly stringent emission standards but still exceeded laboratory emission limits, albeit at much lower exceedance levels (up to 0.21 g/km) than their diesel counterparts (up to 0.57 g/km).

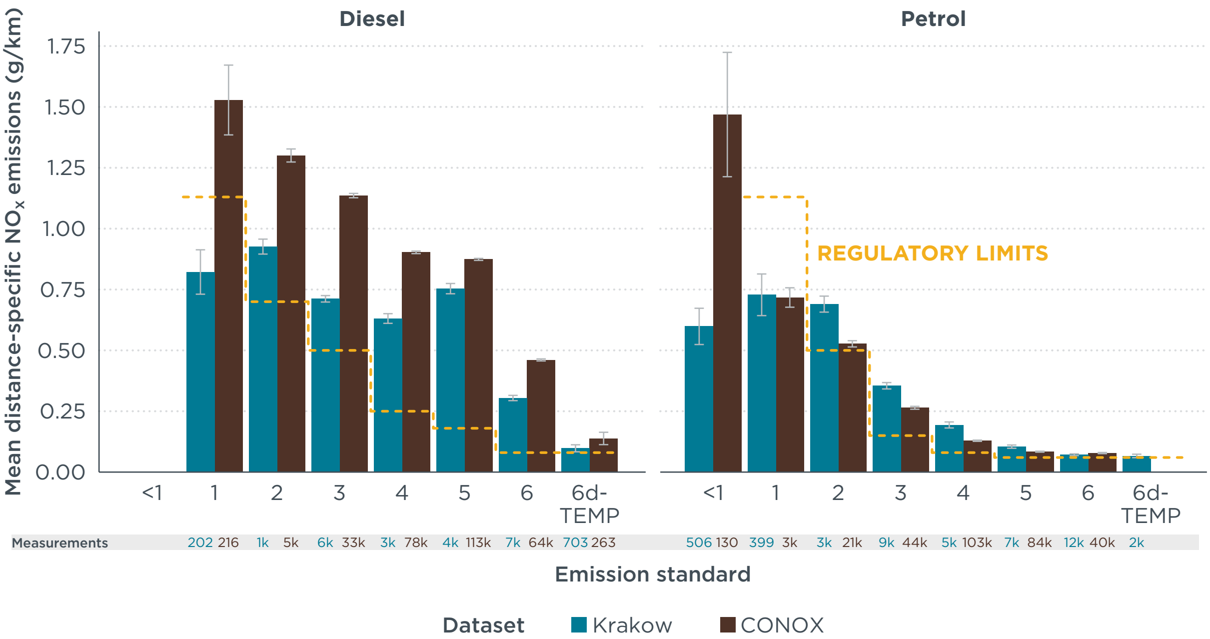


Figure 6. Mean estimated distance-specific NO_x emissions from diesel and petrol passenger cars, grouped by emissions standard, for Krakow and CONOX remote sensing data. The number of measurements is presented below each bar. Whiskers represent the 95% confidence interval of the mean. Results are only shown for groups with at least 100 measurements.

With average NO_x emissions below 0.1 g/km, diesel Euro 6d-TEMP passenger cars in Krakow came close to the regulatory limits of 0.08 g/km and were well within the not-to-exceed limit of 0.168 g/km for on-road measurements. Figure 7 plots the average distance-specific NO_x emissions of Euro 6d-TEMP passenger cars by fuel type and vehicle make. On average, diesel vehicles emitted 0.033 g/km (51%) more than petrol vehicles. Virtually all vehicle makes met the not-to-exceed limit for on-road real-driving emissions measurements of 0.168 g/km for diesel vehicles and 0.126 g/km for petrol vehicles. Approximately half of the makes also met the laboratory type-approval limit of 0.08 g/km for diesel vehicles and 0.06 g/km for petrol vehicles. Due to the small sample sizes, estimates of the mean remain uncertain, as witnessed by the wide ranges in 95% confidence intervals. Moreover, measurements at different engine loads and under varying driving conditions are needed to assess the external validity of these results.

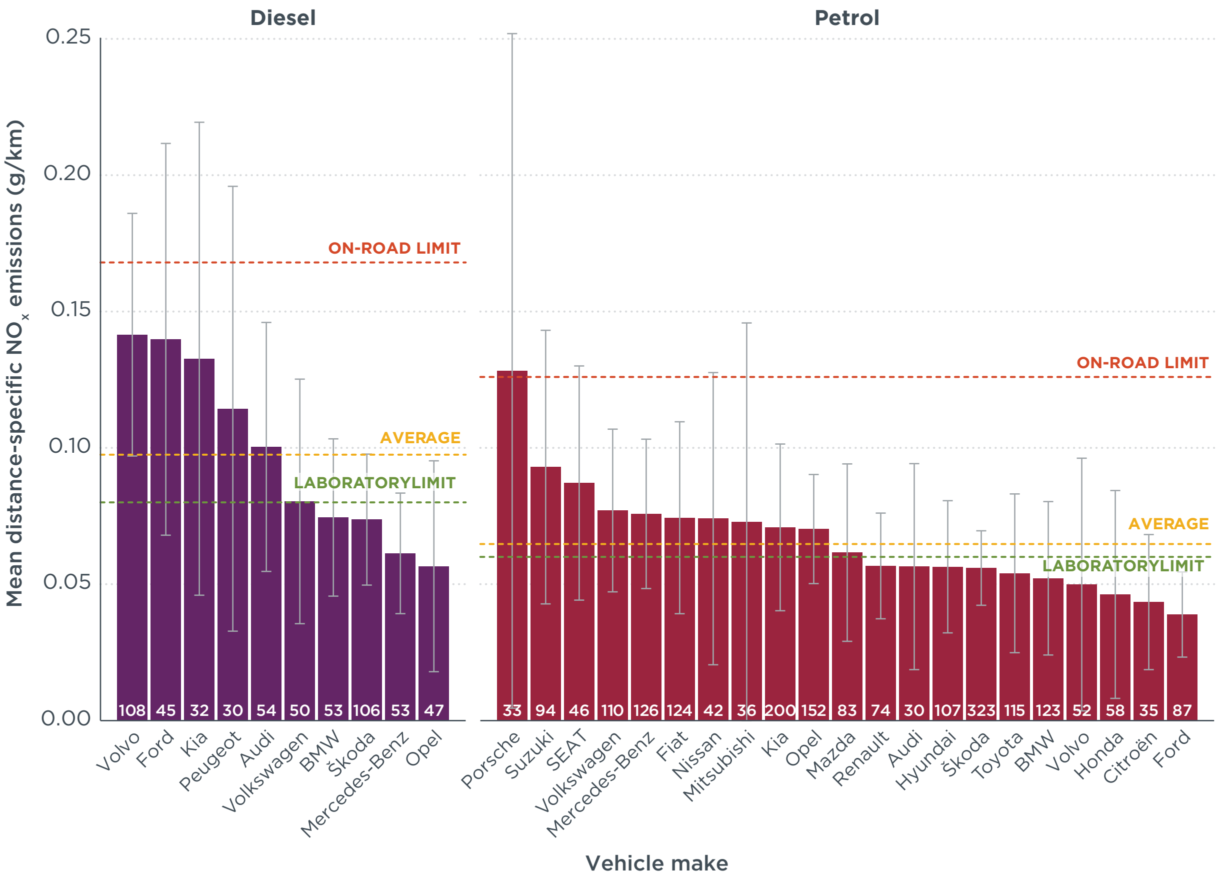


Figure 7. Mean distance-specific NO_x emissions from Euro 6d-TEMP passenger cars, grouped by fuel type and make, for Krakow remote sensing data. The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean. Results are only shown for groups with at least 30 measurements.

Figure 8 plots the estimated share of NO_x emissions from passenger cars and the share of measurements by fuel type and emissions standard. Most diesel passenger cars and petrol cars predating the Euro 3 standard have a higher share of NO_x emissions than share of vehicles measured. Euro 4 diesel passenger cars have the highest share of NO_x emissions, approximately 20%, but account for only 12% of measurements. Diesel vehicles represent 40% of measurements and accounted for approximately 65% of total NO_x emissions. Even so, the impact of diesel passenger cars on total NO_x emissions is lower in Krakow than in other recent European remote sensing campaigns, such as the 2018 Paris campaign, due to the higher share of pre-Euro 4 petrol passenger cars in Krakow.

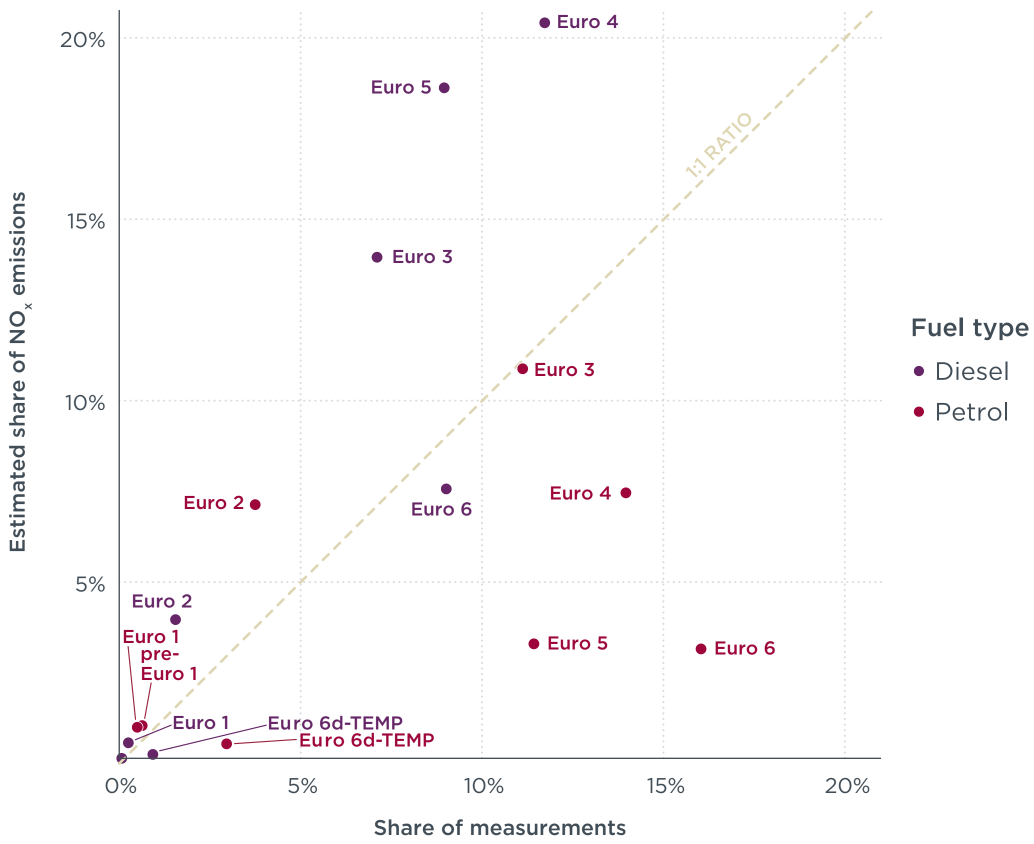


Figure 8. Share of measurements and estimated share of total NO_x emissions in Krakow from passenger cars by emissions standard and fuel type. The share of remote sensing measurements is considered as a crude proxy of vehicle-kilometers travelled by each group of vehicles

Figure 9 presents the average fuel-specific NO_x emissions from light commercial vehicles by fuel type and emission standard, comparing levels in Krakow and CONOX data. The emission levels and trends over time are similar to the passenger car results presented in Figure 4: diesel emission levels were relatively unaffected by Euro standards 1–5 while petrol NO_x emissions declined. The results for petrol vehicles are sparse because the vast majority of light commercial vehicles are diesel-fueled.[22] Similar to the passenger car results, diesel NO_x emissions were lower and petrol NO_x emissions were higher in Krakow than in CONOX. The reasons for the differences are likely the same as for passenger cars: the lower power demand and warm weather explain the lower diesel emissions, and the age of the Krakow petrol fleet explains the higher petrol emissions. Only 48 measurements of Euro 6d-TEMP light commercial vehicles were collected in Krakow and are thus not shown in the figure. An explanation for that low number is that the emissions standard for light commercial vehicles is being phased-in from September 2018 to September 2020, one year later than for passenger cars.

22 Georg Bieker, Uwe Tietge, Felipe Rodriguez, and Peter Mock, "European Vehicle Market Statistics, 2019/2020" (ICCT: Washington, D.C., 2019), https://theicct.org/publications/european-vehicle-market-statistics-20192020.

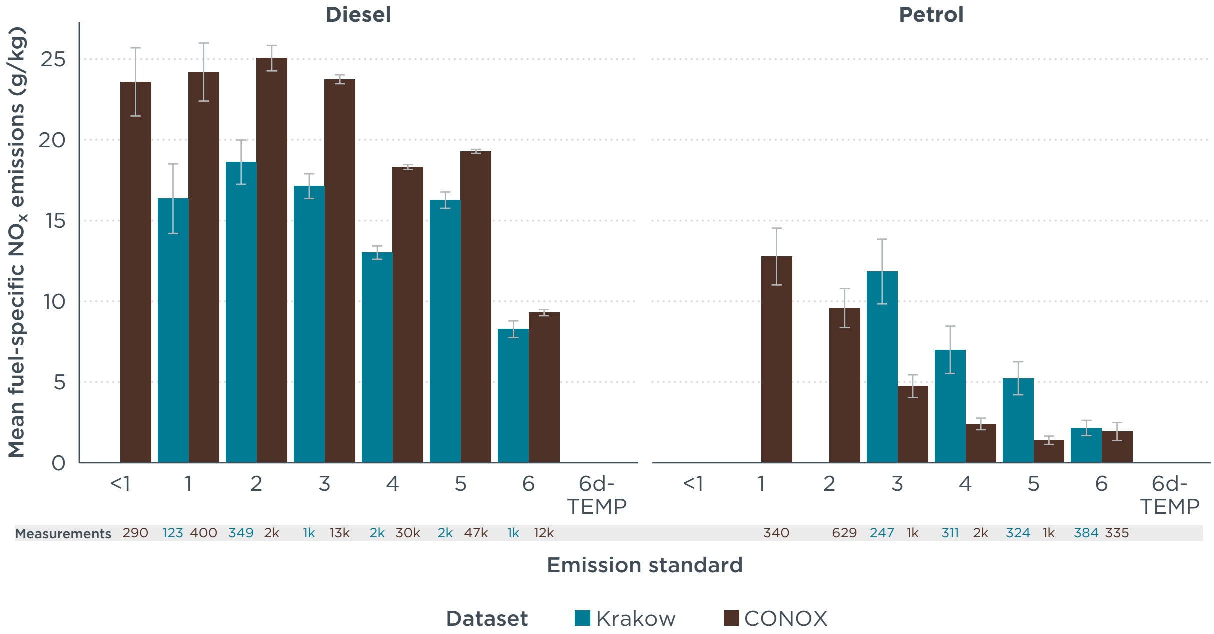


Figure 9. Mean fuel-specific NO_x emissions from diesel and petrol light commercial vehicles, grouped by emissions standard, for Krakow and CONOX remote sensing data. The number of measurements is presented below each bar. Whiskers represent the 95% confidence interval of the mean. Results are only shown for groups with at least 100 measurements.

LIGHT-DUTY VEHICLE CARBON MONOXIDE EMISSIONS

Figure 10 and Figure 11 present average fuel-specific carbon monoxide (CO) emissions from passenger cars and light commercial vehicles, respectively. The results are grouped by fuel type and emissions standard and compare emission levels in Krakow and CONOX. As in previous remote sensing campaigns, CO emissions from petrol vehicles in Krakow decrease with more stringent emission standards, while emissions from diesel vehicles historically have been comparatively low. Average CO emissions from Euro 6 petrol passenger cars were approximately 23% higher than their diesel counterparts. The discrepancy is larger for light commercial vehicles, with petrol Euro 6 vehicles in Krakow emitting more than double the amount of CO as diesel vehicles. This difference is likely rooted in emission standards, which allow Euro 6 petrol passenger cars to emit twice as much CO as their diesel counterparts during type approval, while petrol light-commercial vehicles are allowed to emit up to three times as much CO as their diesel counterparts.

Figure 10 and Figure 11 also indicate that CO emissions were considerably higher in Krakow than in previous CONOX campaigns. For passenger cars, this difference is particularly notable for Euro 1–4 vehicles. Vehicle deterioration likely explains the difference between Krakow and CONOX results, as Krakow petrol vehicles were significantly older than CONOX vehicles (see Table 1) and CO emissions have been shown to increase with vehicle age.[23]

23 Dallmann et al., *Remote Sensing of Motor Vehicle Emissions in Paris*; Dallmann et al., *Remote Sensing of Motor Vehicle Emissions in London*; Borken-Kleefeld and Chen, "New Emission Deterioration Rates for Gasoline Cars – Results from Long-Term Measurements."

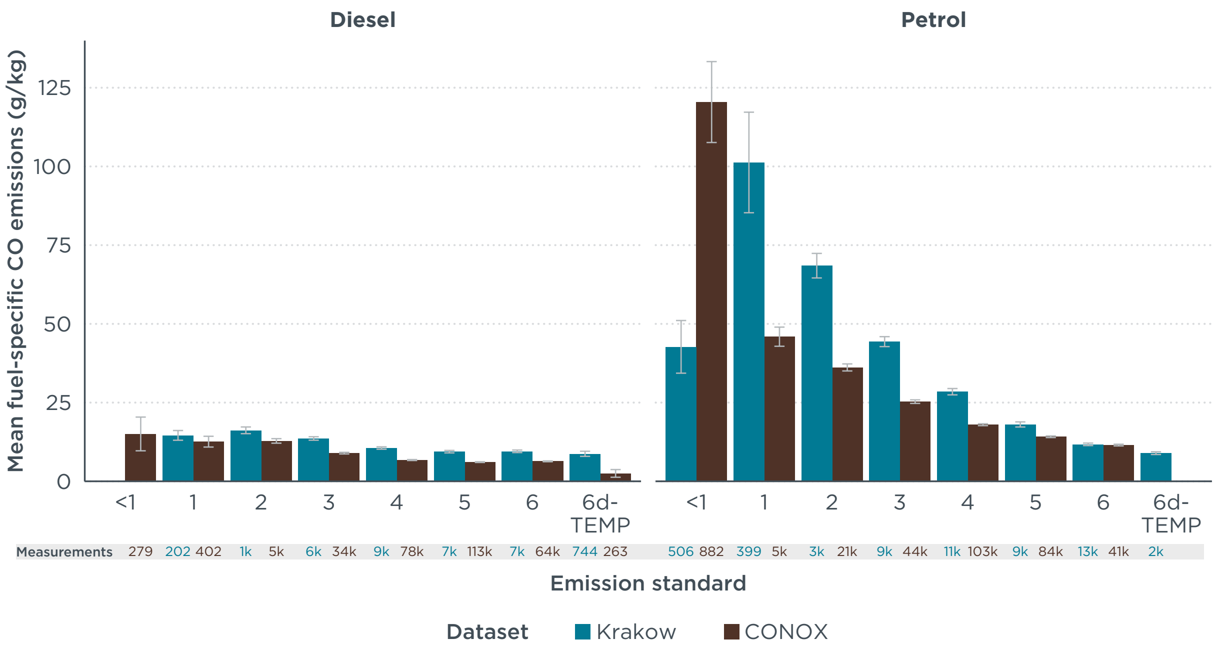


Figure 10. Mean fuel-specific CO emissions from diesel and petrol passenger cars, grouped by emissions standard, for Krakow and CONOX remote sensing data. The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean. Results are only shown for groups with at least 100 measurements.

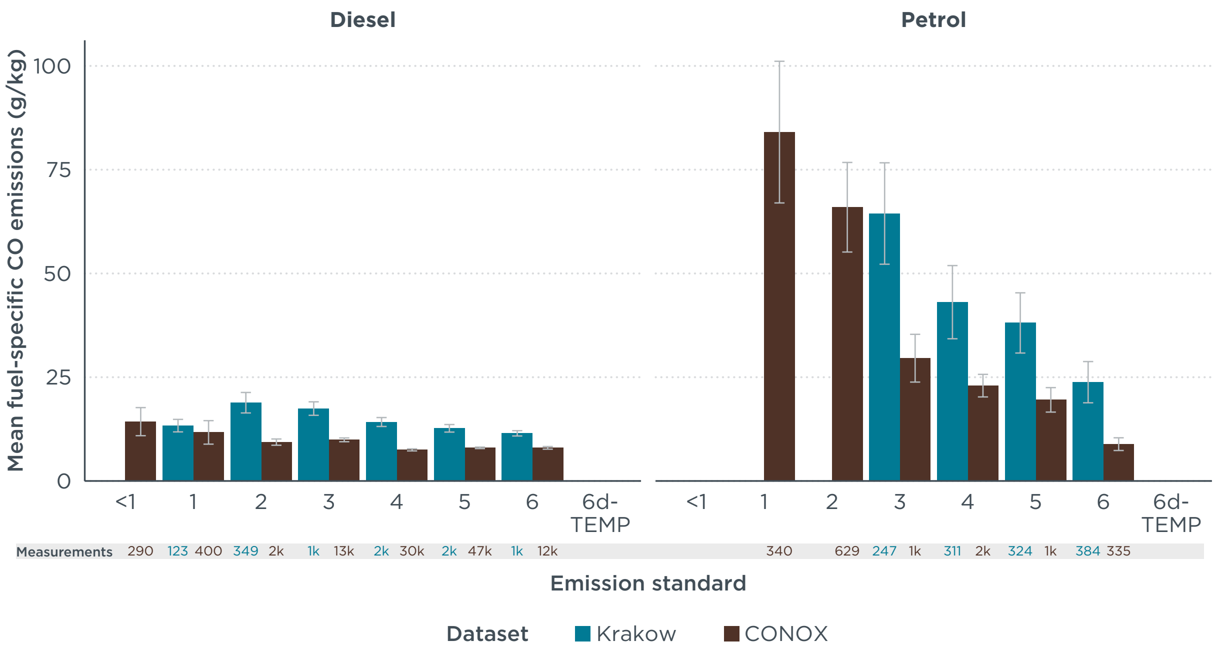


Figure 11. Mean fuel-specific CO emissions from diesel and petrol light commercial vehicles, grouped by emissions standard, for Krakow and CONOX remote sensing data. The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean. Results are only shown for groups with at least 100 measurements.

LIGHT-DUTY VEHICLE PARTICULATE MATTER EMISSIONS

The Opus RSD5000 remote sensing instrument used in the Krakow campaign measures exhaust plume opacity as a proxy for particulate matter (PM) emissions. The opacity measurement provides some information about particulate matter emissions, but it is fundamentally different than methods used to quantify particulate matter mass and particle number emissions in regulatory certification and compliance testing. In general, the opacity measurement is useful for evaluating PM emissions from older diesel and high-emitting vehicles. The approach is less useful for quantifying PM emissions from properly functioning petrol vehicles and modern diesel vehicles equipped with particulate filters, as exhaust opacity readings for these vehicles are expected to fall within the noise band of the instrument. The method also does not permit the measurement of the number of particles, which is regulated in addition to their mass since the implementation of Euro 5b for diesel and Euro 6 for gasoline direct injection.

Figure 12 and Figure 13 show average PM emissions from passenger cars and light commercial vehicles, respectively. Results are grouped by fuel type and emissions standard and compare emission levels in Krakow and CONOX. Note that opacity measurements from the 2018 campaign in Paris were not included in the CONOX average because the Paris measurements were collected using the Hager Environmental & Atmospheric Technologies (HEAT) Emissions Detection and Reporting (EDAR) instrument,[24] and results are not directly comparable with Opus RSD5000 measurements.[25] The omission of the Paris measurements removed all PM measurements of Euro 6d-TEMP vehicles in the CONOX data. In Krakow, as in CONOX, PM emissions from diesel Euro 5 and Euro 6 vehicles are similar to modern petrol vehicles and close to the detection level of remote sensing instruments. Conversely, PM emissions from pre-Euro 5 diesel passenger cars and light commercial vehicles were clearly detectable using remote sensing instruments. The Krakow emission levels were found to be consistently lower than CONOX averages.

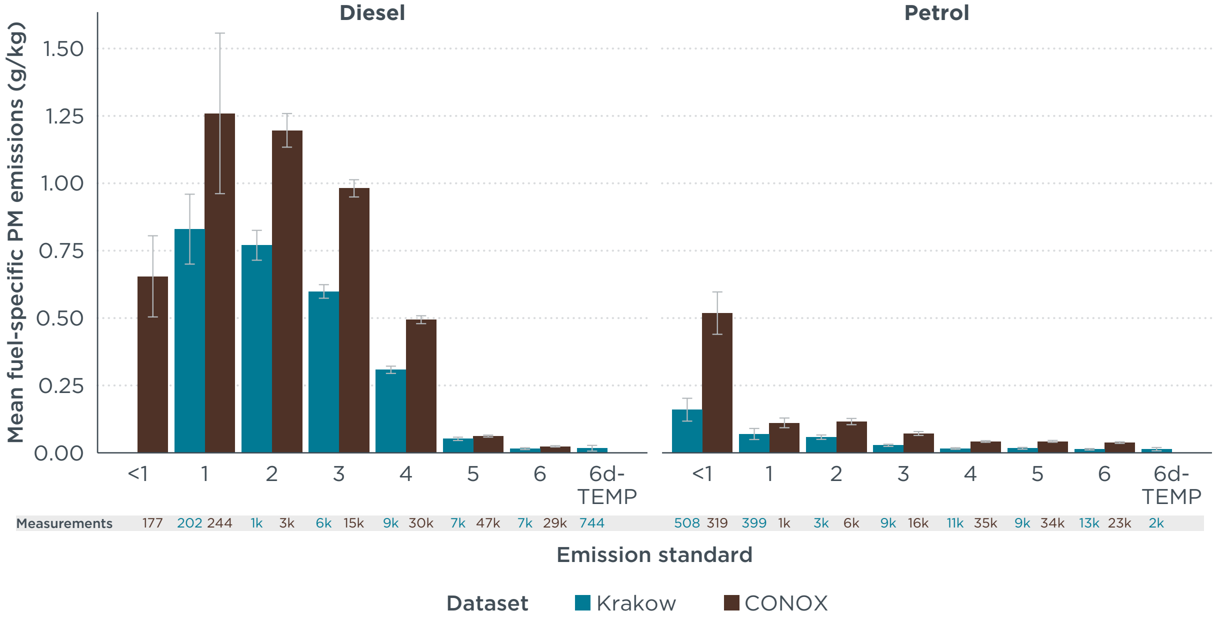


Figure 12. Mean fuel-specific PM emissions from diesel and petrol passenger cars, grouped by emissions standard, for Krakow and CONOX remote sensing data. The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean. Results are only shown for groups with at least 100 measurements.

24 see Karl Ropkins et al., "Evaluation of EDAR Vehicle Emissions Remote Sensing Technology," *Science of The Total Environment 609* (December 2017): 1464–74, https://doi.org/10.1016/j.scitotenv.2017.07.137.

25 Dallmann et al., *Remote Sensing of Motor Vehicle Emissions in Paris*.

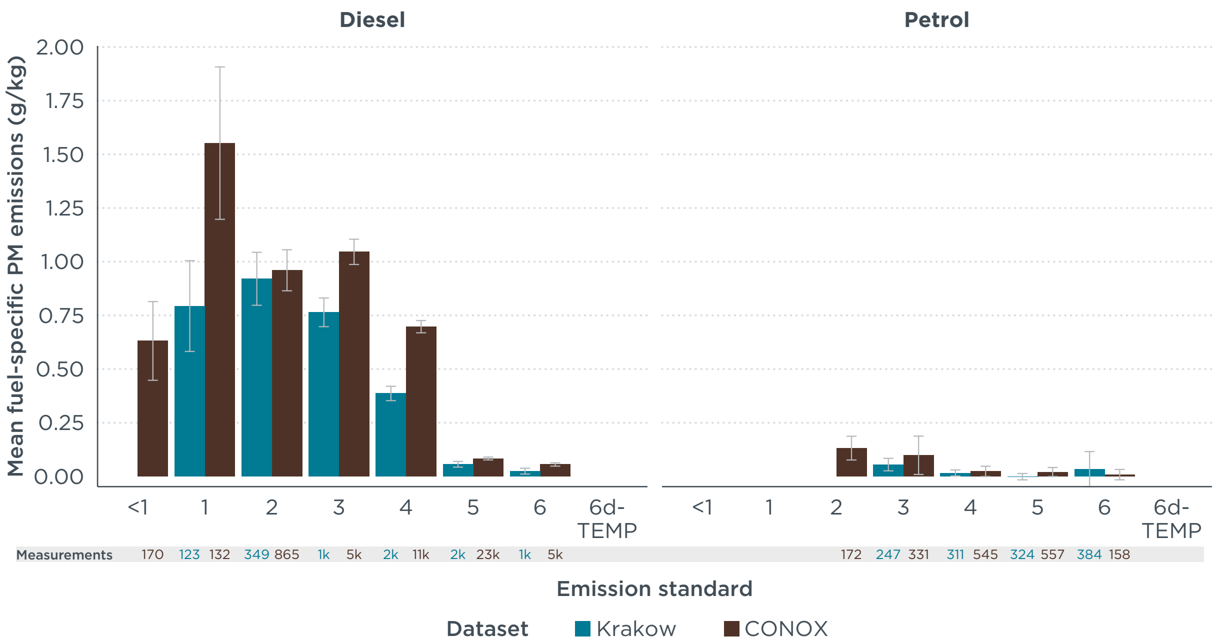


Figure 13. Mean fuel-specific PM emissions from diesel and petrol light commercial vehicles, grouped by Euro standard, for Krakow and CONOX remote sensing data. The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean. Results are only shown for groups with at least 100 measurements.

Figure 14 investigates the differences in PM emissions from diesel passenger cars between the Krakow and CONOX datasets. The figure explores the relation between VSP and PM emissions per emissions standard using generalized additive models. The VSP ranges are truncated, from the 5th to 95th percentile per group, to avoid plotting relationships for ranges with scarce data. For Euro 5 and Euro 6 diesel vehicles, the figure indicates that PM emissions are low across all levels of VSP, in line with the excepted filtering performance of wall-flow diesel particulate filters (DPFs). For Euro 1–4 vehicles, emissions increase with VSP up to approximately 15 kW/ton in the CONOX data and for the full range of VSP in the Krakow data. This upward trend appears consistent with the diffusion flame combustion—the fuel burns as it gets in contact with air present in excess—of diesel, which typically requires a higher fuel-to-air ratio with increased engine load. The lack of oxygen in the combustion chamber occurring at higher power results in poorer fuel combustion and accelerated particulate formation. Judging by the average PM emissions and VSP (see round markers), adjusting for VSP accounts for more than half of the difference between CONOX and Krakow measurements for Euro 1–4 vehicles. Nevertheless, some differences between CONOX and Krakow PM emission levels remain unexplained.

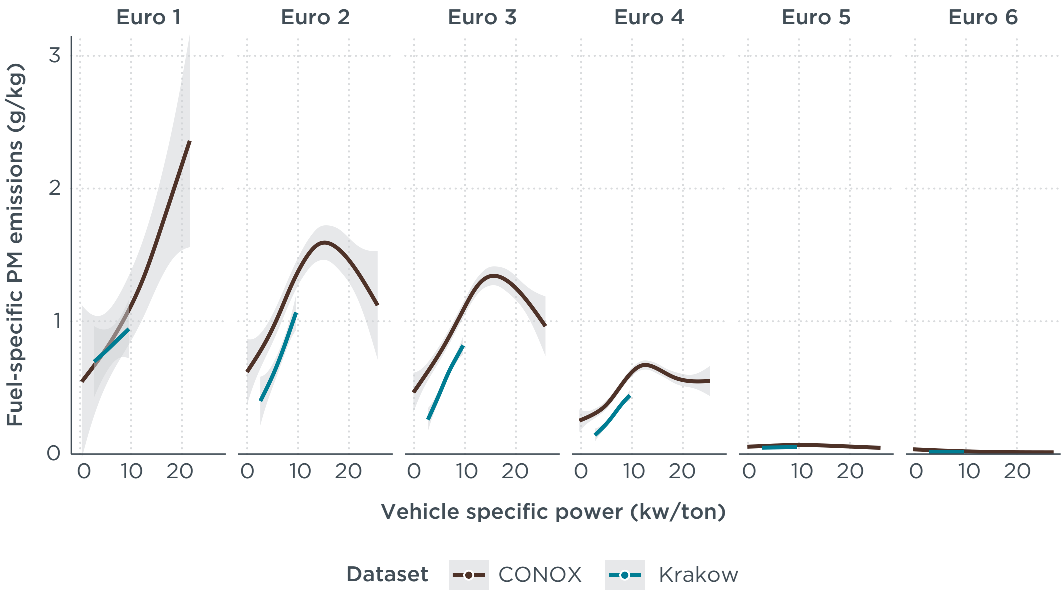


Figure 14. Comparison of fuel-specific PM emissions from Euro 1 through Euro 6 diesel passenger cars as a function of VSP in Krakow (blue) and CONOX (brown). The relationship between PM emissions and VSP is represented using generalized additive models with 95% confidence intervals. Round markers represent mean PM emissions and VSP.

CASE STUDY: TAXIS

This case study examines the remote measurements of the taxi fleet in Krakow. Compared with passenger cars, taxis comprise a small fraction of the overall number of light-duty vehicles, but their comparatively high annual mileage means that they represent a disproportionate share of overall emissions. In the Krakow remote sensing campaign, taxis accounted for approximately 3%, or 2,300 out of 78,000, of passenger car measurements.

Figure 15 compares the taxi fleet composition in terms of fuel type and emissions standard with other passenger cars. Taxis were, on average, 6 months older than other passenger cars, with an average age of 9.7 years compared with 9.1 years. This difference correlates with the average Euro standard of vehicles across the fleet, with taxis being biased towards the older standards than other passenger cars. In addition, the taxi fleet had a higher share of diesel vehicles, with the majority (55%) of taxis being diesel-fueled and the majority (61%) of passenger cars being petrol-fueled. Taken together, Euro 4–5 diesel and Euro 3 petrol vehicles are significantly more common as taxis than they are passenger cars.

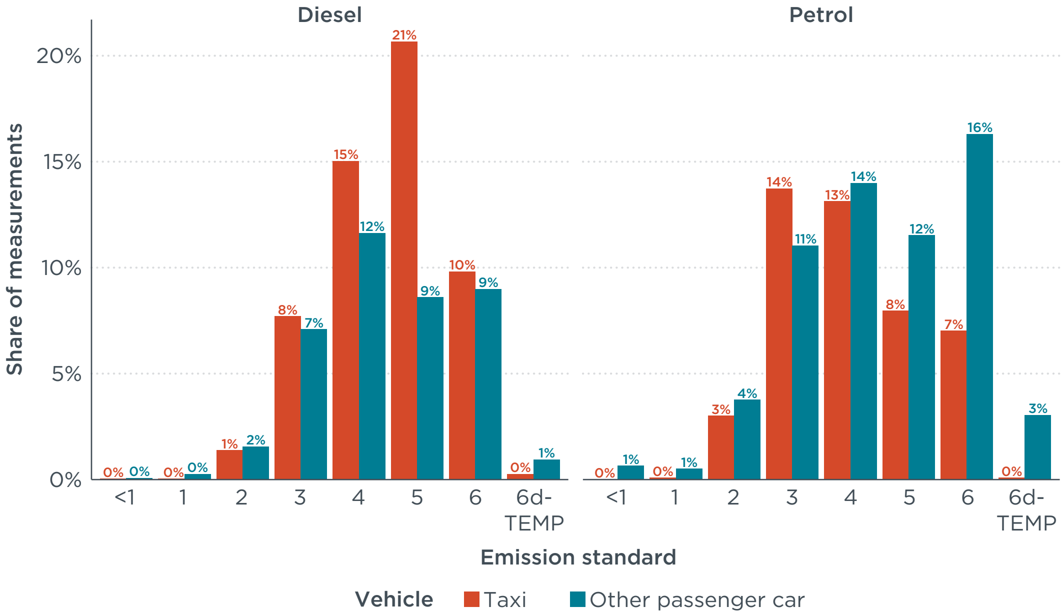


Figure 15. Comparison of Krakow taxi and other passenger car measurements in terms of fuel type and emission standard.

Figure 16 presents mean fuel-specific CO, NO_x, and PM emissions across the taxi and passenger car fleets, for the entire fleets and by emission standard and fuel type.

Fleet-wide average NO_x emissions from taxis were 59% higher than from passenger cars, and were higher across all fuel type and emissions standard combinations except diesel Euro 2 and diesel Euro 6. Petrol taxis display higher NO_x emissions than other petrol passenger cars across all generations of emission standards, and the disparity widens with age. Assuming that taxis are driven more than other passenger cars, this trend is consistent with deterioration of catalytic converters over time, particularly in vehicles type-approved to older emission standards.[26] Pre-Euro 6 diesel vehicles do not rely as heavily on these devices to reduce NO_x emissions, which could explain the seemingly reduced impact of mileage on NO_x emissions.

Euro 6 taxis are the only diesel vehicles for which NO_x emissions are notably lower than their passenger car counterparts. NO_x reduction strategies within modern diesel engines vary widely in both design and efficacy across different manufacturers,[27] and it is likely that the dominance of certain brands in the taxi fleet had an impact on these figures. Vehicles manufactured by Mercedes-Benz represented close to 60% of all measured Euro 6 diesel taxis, compared to less than 18% of other Euro 6 diesel passenger cars. NO_x emissions from Mercedes-Benz vehicles were, on average, 70% lower than from other Euro 6 diesel passenger cars in Krakow.

The results display less discrepancies between taxis and other passenger cars when it comes to CO and PM emissions. In terms of CO emissions, diesel vehicles make up the majority of the taxi fleet and, as shown in Figure 10 and Figure 16, emit less CO than petrol vehicles. By contrast, although petrol taxis are a minority of the taxi fleet, the mileage-related degradation of exhaust aftertreatment systems means, as with NO_x emissions, that they generally emit more CO than other passenger cars. Fleet-wide PM emissions are close to the detection limit of remote sensing instruments.

26 Borken-Kleefeld and Chen, "New Emission Deterioration Rates for Gasoline Cars – Results from Long-Term Measurements."

27 Vicente Franco, Francisco Posada Sánchez, John German, and Peter Mock, *Real-World Exhaust Emissions from Modern Diesel Cars*, (ICCT: Washington, D.C., 2014), http://www.theicct.org/real-world-exhaust-emissions-modern-diesel-cars.

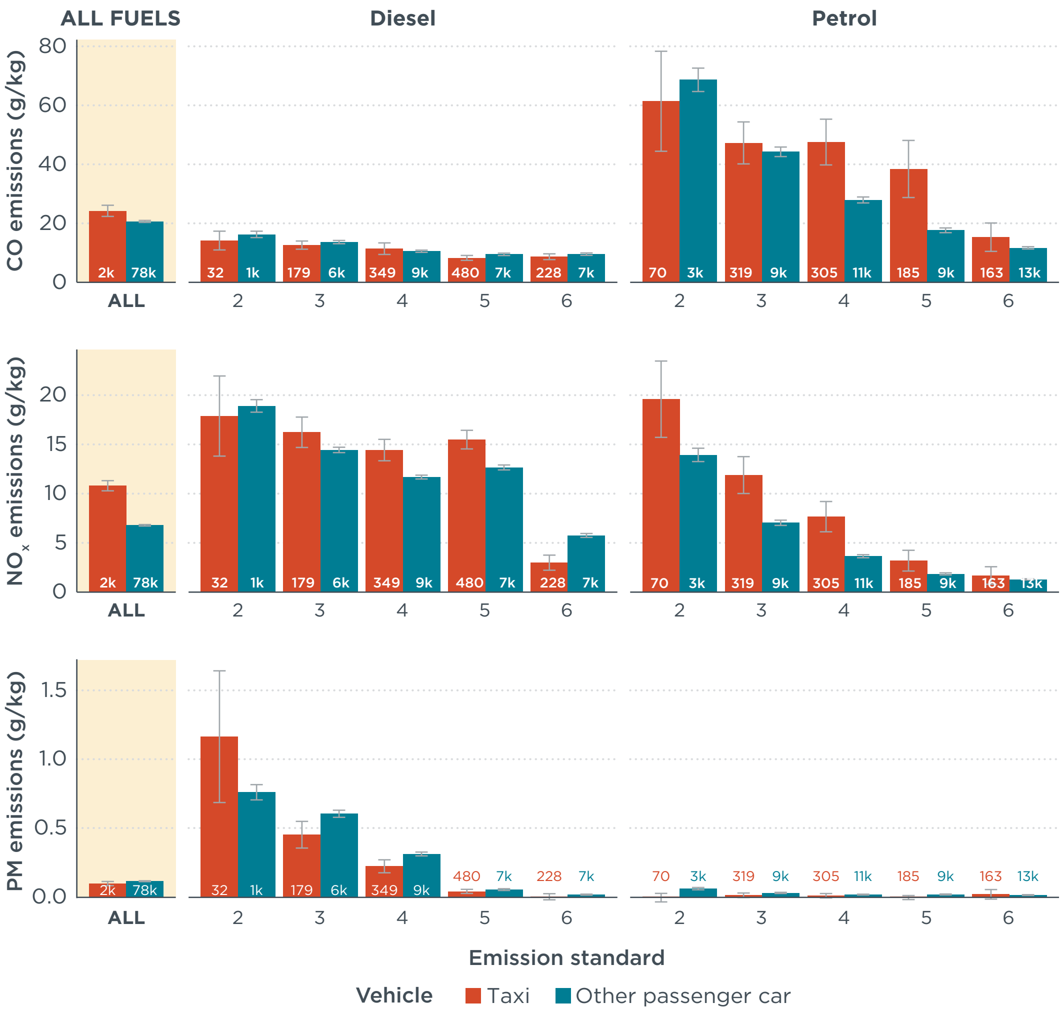


Figure 16. Mean fuel-specific CO, NO_x, and PM emissions from Krakow taxis and other passenger cars in total and by fuel type and emissions standard. The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean.

CASE STUDY: BUSES

This case study focuses on buses measured in the Krakow remote sensing campaign. Both publicly-owned services and privately-managed commercial fleets operate in the city. This latter category is split into two types—those which are listed in the municipal registry and those which are not.

The data at hand did not allow for a clear differentiation of buses by vehicle category or weight class. We therefore grouped buses by body type based on model names. The body types include coaches (buses designed for long routes), transit buses (buses designed for shorter routes), and vans/minibuses. The latter group is typically limited to fewer than 20 passengers and are either type-approved to light-duty vehicle (LDV) or heavy-duty vehicle (HDV) emission standards, depending on vehicle weight and passenger capacity.

Data on emission standards have been combined from a variety of sources, including the Krakow Public Transport Authority records and the national vehicle registry. Where data were not available from these sources, the emission standard was estimated based on the vehicle registration date. This mainly applies to those vehicles of unknown ownership. Because the weight and passenger capacity of some vans/minibuses is unknown, we use both light-duty (Arabic numerals) and heavy-duty (Roman numeral) emissions standard notations in the figures. All buses in this case study are diesel-fueled.

Figure 17 presents the number of measurements by body type, emissions standard, and owner type. Virtually all measured municipal buses are operated by the same local authority, which means that fleet renewal will be broadly aligned and implemented in cycles. This could explain why almost all of these vehicles were type-approved to Euro VI.

By contrast, the smaller vans and minibuses fall across a range of privately-run providers and unknown owners, thus displaying greater variance. The three most common emission standards in vans and minibuses are fairly new Euro 6/VI and comparatively old Euro 2/II and Euro 3/III vehicles, but with few vehicles type-approved to emission standards between these two extremes. Privately-owned buses skew toward older emission standards.

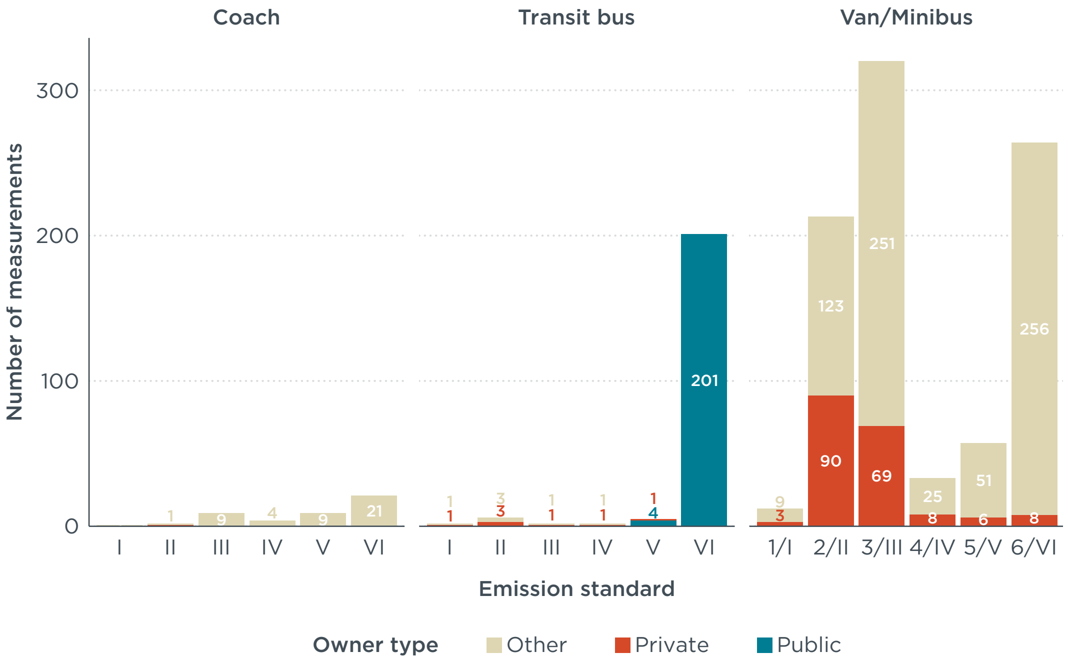


Figure 17. Number of bus measurements by emissions standard, owner type, body type and emission standard.

Figure 18 presents average NO_x and PM emissions by owner type and emissions standard. Similar to light-duty diesel vehicles (see Figure 4 and Figure 9), reductions in fuel-specific NO_x emissions were most prominent with the introduction of Euro 6/VI. Euro 6/VI buses emitted 81%–97% less NO_x than Euro 2/II buses and 72%–94% less NO_x than Euro 5/V buses. Differences between publicly and privately-owned Euro 6/VI buses could be explained by a significant fraction of the latter vehicles being certified to the Euro 6 LDV regulation, while public transit buses due to their higher mass were type-approved to the HDV Euro VI procedure. It is widely accepted that Euro VI HDV regulations were more effective than their LDV counterparts in reducing real-world NO_x emissions compared to Euro 5/V standards.[28]

PM emissions underwent a more gradual decline than NO_x emissions. The Euro 4/IV and 5/V standards generated an increase of measures targeting PM emissions, resulting in a decrease between 4/IV and 5/V compared with 2/II and 3/III. There is another notable

28 Rachel Muncrief, *NOx Emissions from Heavy-Duty and Light-Duty Diesel Vehicles in the EU: Comparison of Real-World Performance and Current Type-Approval Requirements*, (ICCT: Washington, D.C., 2017), https://theicct.org/publications/nox-emissions-heavy-duty-and-light-duty-diesel-vehicles-eu-comparison-real-world.

drop in PM emissions with the implementation of Euro VI, when DPFs effectively became industry-standard for compliance with the regulation which sought to reduce overall particulate mass and number.[29]

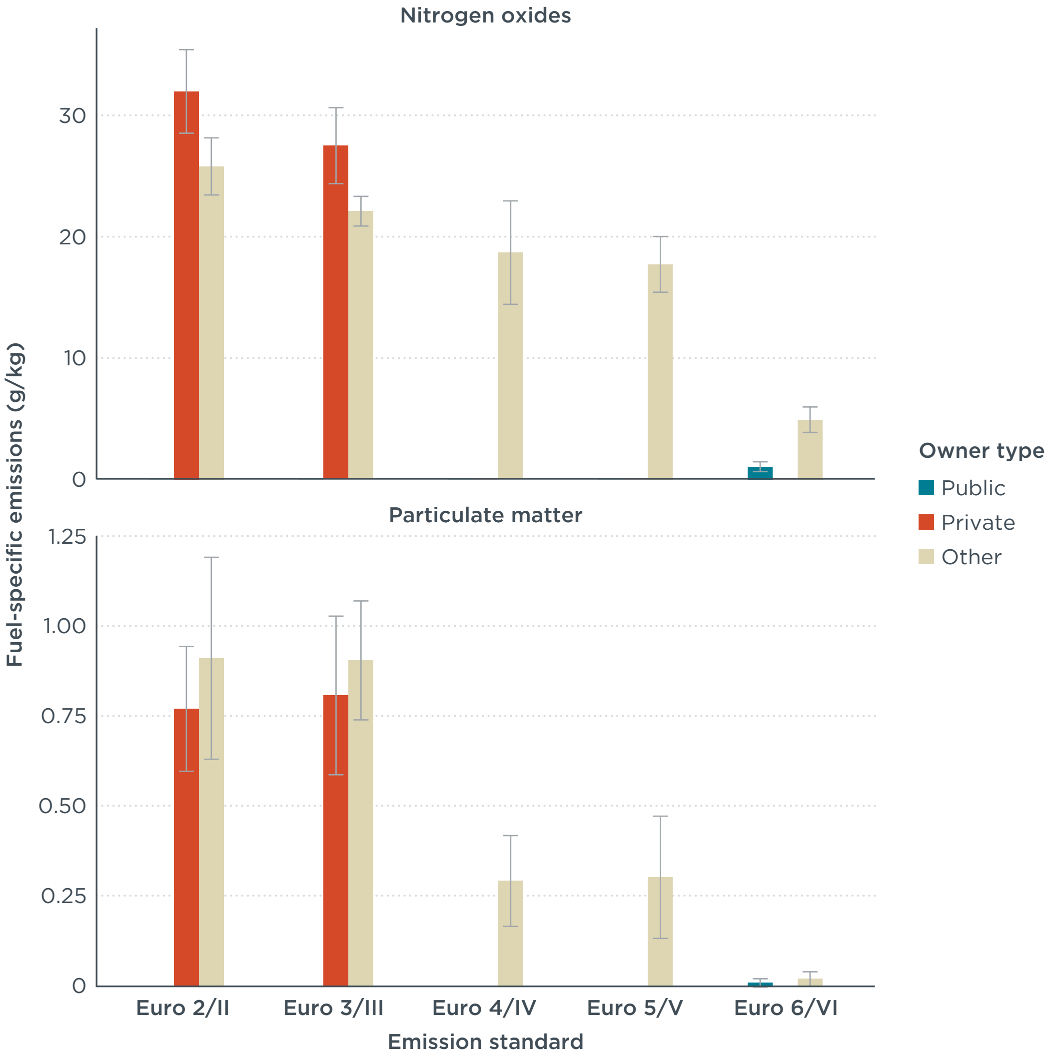


Figure 18. Fuel-specific NO_x and PM emissions of public, private, and other buses by emissions standard. Results are only shown for groups with at least 30 measurements.

There are two limitations to our findings that should be acknowledged. First, in the absence of fuel consumption data for buses, pollutant emissions per unit of distance driven and passenger-distance are unknown, impeding comparisons across vehicles that vary in size from light-duty vans to heavy-duty transit buses. Second, light-duty and heavy-duty emission test procedures and emission limits are inherently difficult to compare, thus again impeding comparisons across different categories of buses. Nevertheless, the results point toward the general efficacy of the Euro 6 and Euro VI regulations in delivering substantial emission reductions compared with previous generations of emission standards.

29 Tim Dallmann and Lingzhi Jin, *Fuel Efficiency and Climate Impacts of Soot-Free Heavy-Duty Diesel Engines*, (ICCT: Washington, D.C., 2020), https://theicct.org/publications/soot-free-hd-diesel-engines-jun2020.

CASE STUDY: DIESEL PASSENGER CARS WITH HIGH PM MEASUREMENTS

This section studies individual PM measurements of the highest emitting fraction of diesel passenger cars. As discussed in the proceeding case study, DPF became an industry-standard solution to drastically reduce particulate emissions from post-Euro 4 diesel light-duty vehicles. However, anectodical evidence suggests that poor maintenance, ageing, or deliberate tampering or removal of the DPF in post-Euro 4 vehicles may lead to high-emitting vehicles that should ordinarily emit little PM.[30] In contrast, only a few cars type-approved to Euro 4 or earlier standards were equipped with a filter.

Figure 19 compares the cumulative distribution of fuel-specific PM—emissions per amount of fuel burnt—from Euro 2 to Euro 6d-TEMP diesel passenger cars in Krakow. The fact that the distributions of successive emissions standard barely overlap indicates that newer vehicles provide an overall decrease in PM emissions. In particular, Euro 5 and Euro 6 PM measurements clearly outperform those of pre-Euro 5 cars.

The right panel of the figure shows individual emission measurements of vehicles in the 95th to 100th percentiles, which corresponds to 5% of the highest PM values by emission standard. PM emission levels remain relatively flat up to the 99th percentile for Euro 5 vehicles and up to the 99.9th percentile for Euro 6 and 6d-TEMP. Approximately 6% of Euro 5 measurements and 3% of Euro 6 and 6d-TEMP measurements exceed Euro 3 median emissions. In other words, only a small fraction Euro 5 and 6 passenger car measurements present PM levels comparable to vehicles typically not equipped with a DPF.

The small share of vehicles emitting high levels of PM does not suggest that DPF malfunction or tampering does not occur, but that it is unlikely to be a widespread issue leading to excess particulate emissions in Krakow. Rather than suffering from outright failure or tampering, some DPFs may experience microfractures. This malfunction could lead to abnormal levels of particulate numbers (PN) in the nanometer size range that remote sensing instruments used in Krakow would be ill-equipped to detect.

30 Transport & Environment, "How to Tackle the Illegal Diesel Filter Removal 'industry' in Belgium and Beyond," July 3, 2017, https://www.transportenvironment.org/news/how-tackle-illegal-diesel-filter-removal-industry-belgium-and-beyond.

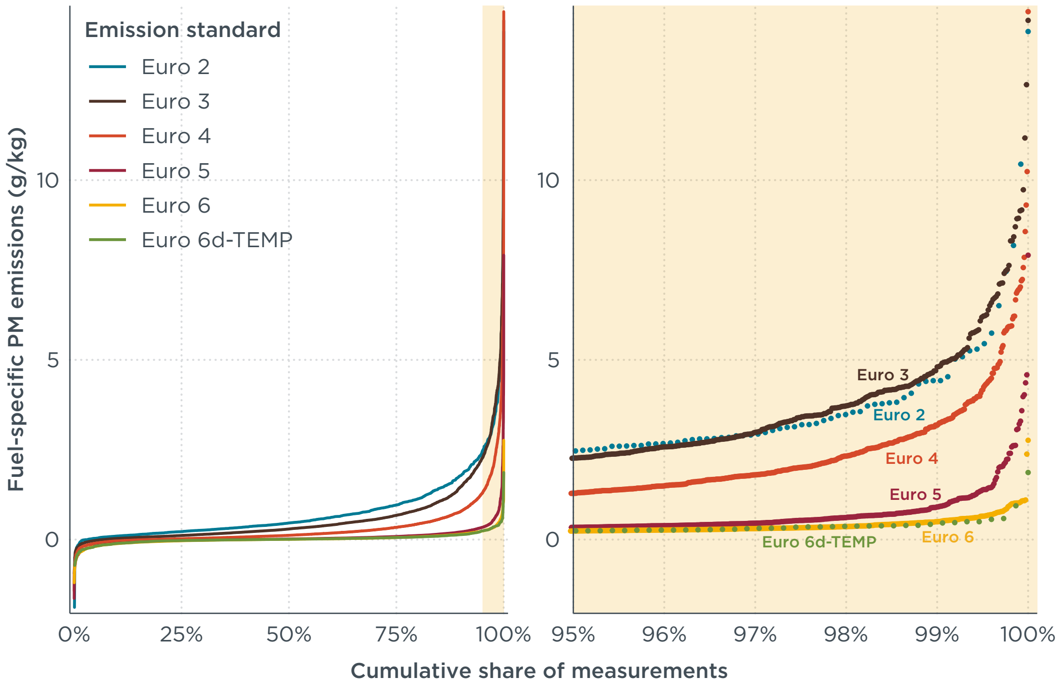


Figure 19. Cumulative distribution of diesel passenger car fuel-specific PM emissions by emissions standard. Left panel: Full range. Right panel: 95th to 100th percentile.

CONCLUSION

The 2019 Krakow remote sensing campaign is unique in multiple aspects, including being the first emissions measurement program of its kind in Poland, a country where vehicle age is among the highest in Europe. This context is reflected in the city's comparatively high overall vehicle age, although the figure is still lower than the national average. The Krakow campaign was also conducted after the introduction of Euro 6d-TEMP standards, and thus provided an opportunity to gather much-needed empirical data on vehicles type-approved to the latest emissions regulation. Finally, the test conditions themselves were also notable, with the warmest ambient temperature among all CONOX campaigns and lower-than-average engine loads.

Overall, NO_x emissions from diesel passenger cars measured in Krakow were lower than in other European cities. This difference can be explained by favorable ambient temperatures and comparatively low engine load conditions. NO_x emissions from older petrol vehicles were generally somewhat higher than those in other datasets, a finding likely explained by the older fleet in Krakow. The NO_x emissions from diesel vehicles remain generally several times higher than emissions from petrol vehicles of equivalent emission standards, with the exception of Euro 6d-TEMP passenger cars. The NO_x emissions from this class were within regulatory on-road limits, and almost within the Euro 6 laboratory type-approval limit, however they nevertheless remained 50% above petrol equivalents although measurement conditions in Krakow favored lower emissions. The estimated share of total NO_x emissions from passenger cars by fuel type and emissions standard suggests that the highest contributors are diesel vehicles and petrol cars predating the Euro 3 standard.

Similar to findings from previous campaigns in London and Paris, CO emissions from light-duty petrol vehicles show a decrease in-line with advancing emission standards, while diesel CO emissions have remained consistently low and relatively stable. However, the data from Krakow suggests that CO emissions from petrol vehicles were considerably higher than in previous campaigns, with a greater number of older vehicles in service being the likely cause. In addition, Euro 6 light-commercial petrol vehicles emitted more than double the amount of CO than their diesel counterparts. This is probably linked to regulatory CO limits, which are 3 times less stringent than equivalent diesel rules.

Unsurprisingly, pre-Euro 5 diesel passenger cars and light commercial vehicles exhibited the highest PM emission levels. Moreover, Krakow emission levels were consistently lower than the averages from other campaigns, a phenomenon which is partially explained by the test conditions favoring lower engine load.

The Krakow remote sensing campaign has confirmed some lessons learned from previous testing campaigns in Western European cities, as well as revealed some new insights. The campaign revealed that urban NO_x emissions from diesel engines generally exceed petrol levels by several times, or at best by 50% for the newest vehicles. In addition, we found the oldest vehicles contribute disproportionately to air pollution levels due to more lenient emission standards. This is further compounded by the general deterioration of emission reduction strategies through vehicle ageing. The issue of vehicle age is particularly visible in this study. We anticipate the problem to be even more pronounced in the Polish fleet, which is, on average, four years older than that of the Krakow metropolitan area. We therefore recommend that future research investigate fleet emissions in other Eastern European cities with older fleets than the relatively modern fleet of Krakow. Finally, Euro 6d-TEMP vehicles deserve additional and continued attention. Notably, there is currently a lack of real-word measurements at cold ambient temperatures and at higher-load conditions.

As part of the investigation, we developed three case studies. We found little evidence that diesel particulate filter tampering was a widespread problem. In addition, measurement discrepancies between taxis and other passenger car measurements were likely due to the older age of the taxi fleet. Concerning the city's bus fleet, we found that city-run buses in Krakow had the lowest fuel-specific NO_x and PM emission levels, with a majority of vehicles being type-approved to Euro VI standard. This suggests that policy measures aimed at the bus fleet renewal, not just those publicly owned, would thus be an effective means of reducing NO_x and PM emissions in Krakow.

The city of Krakow commissioned this report to inform strategies to mitigate air pollution going forward. The results indicate that a low emission zone focused on phasing out older vehicles—particularly pre-Euro 3 petrol and pre-Euro 6 diesel models—could significantly reduce NO_x emissions and deliver tangible benefits to air quality.

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