ICCT CONSULTING REPORT

Remote sensing of motor vehicle emissions in Krakow

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Acknowledgments

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Introduction

Air pollution in Poland related to fine particulate matter ($PM_{2.5}$), ozone (O_3) and nitrogen dioxide (NO_2) exposure was responsible for over 45 000 premature deaths in 2016.[1] People in Poland are more likely to die from air pollution than the average European Union (EU) resident.[2] The problem is particularly intense in Polish cities, which regularly breach EU air quality limits. Among the 50 cities in the European Union (EU) with the highest 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. Among other contributing factors, and like many countries in the EU, Poland has a high share of diesel-fueled vehicles known to exceed the laboratory certification limits on nitrogen oxides (NO_x) emissions in real-world driving. Moreover, Poland has one of the oldest vehicle fleets in the EU, with an average age of the passenger car fleet in 2018 of 14 years compared to the 11 years EU average.[4] Older vehicles were designed to less stringent emission limits than modern counterparts and are more likely to suffer from emission deterioration.

In response, Poland has adopted the Electric Mobility and Alternative Fuel Law in January 2018. The law includes measures to spur 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 zone of the country. It was implemented in January 2019 for six months and was then extended through September of the same year. The access to the zone was restricted to battery-electric, fuel-cell, and compressed gas vehicles, although it granted exceptions to residents. Although the pilot zone was discontinued, the City of Krakow is willing to implement new policies aiming at reducing vehicle emissions, including projects to implement a low-emission zone.

This study fits into a broader plan of the City of Krakow to tackle traffic-related emissions and discover the most significant culprits. The city’s authorities commissioned a testing campaign in June 2019 to better understand the actual impact of motor vehicle emissions

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[1] EEA, “Air Quality in Europe 2019,” Publication, European Environment Agency, October 2019, https://www.eea.europa.eu/publications/air-quality-in-europe-2019.

[2] “Poland - Air Pollution Country Fact Sheet 2019,” Dashboard (Tableau), European Environment Agency, 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?,” Fall 2019, http://documents.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.

on air quality. Remote sensing instruments were used to measure real-world NO_x, carbon monoxide, and particulate matter emissions of around 100,000 vehicles. Measurements were made remotely via spectroscopy as a vehicle drives 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. This paper starts with providing an overview of the vehicle fleet composition in Krakow. We compare the remote sensing measurements and emissions in Krakow against similar measurements made in other European cities over the past years referred as CONOX[5] that includes data we collected in London[6] and Paris[7]. In particular, the difference for NO_x emissions 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 investigate the share of total NO_x emissions in Krakow from passenger cars by emission standard and fuel type. Two case studies examine emissions from the Krakow's taxis and bus fleet. The last case study scrutinizes particulate matter emissions from diesel passenger cars, focusing on evidence of tampered or malfunctioning particulate filters. The study concludes with policy and research recommendations.

Methodology

Data sources

Remote sensing is a method of non-invasively measuring emissions of vehicles during real-world, on-road operation.[8] Snapshots of the exhaust plume content and driving

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[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.

[6] Tim Dallmann et al., "Remote Sensing of Motor Vehicle Emissions in London" (Washington, D.C.: International Council on Clean Transportation, December 17, 2018), https://theicct.org/publications/true-london-dec2018.

[7] Tim Dallmann et al., "Remote Sensing of Motor Vehicle Emissions in Paris" (Washington, D.C.: International Council on Clean Transportation, September 10, 2019), https://theicct.org/publications/on-road-emissions-paris-201909.

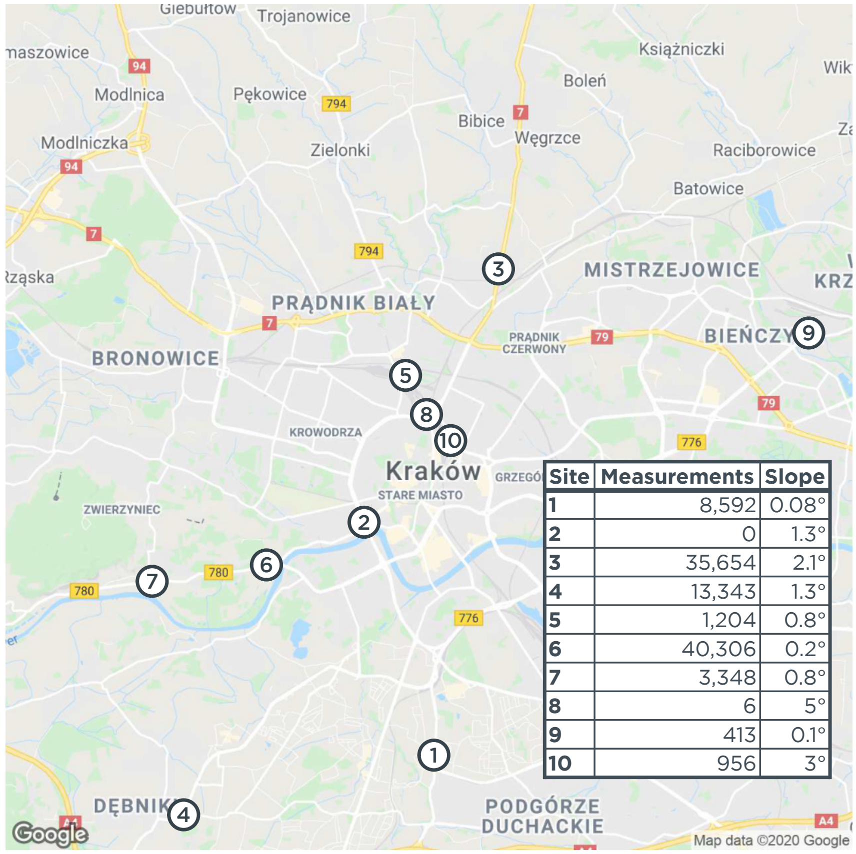
[8] Jens Borken-Kleefeld and Tim Dallmann, "Remote Sensing of Motor Vehicle Exhaust Emissions" (Washington, D.C.: International Council on Clean Transportation, February 1, 2018), https://theicct.org/publications/vehicle-emission-remote-sensing.

conditions, including vehicle speed and acceleration, are collected from passing vehicles at sampling sites. Ambient conditions such as temperature are also recorded. Pictures of the license plate are taken to retrieve technical vehicle characteristics from vehicle registries via the license plate number. 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 personally identifiable information is anonymized in accordance with the General Data Protection Regulation.

Remote sensing measurements commissioned by the municipality of Krakow were collected during 17 measurements days from June 10 to July 1, 2019. Overall, 103,827 measurements were collected using the Opus RSD5000 remote sensing instrument. Details on the campaign are provided in an English report by Opus RSE[9] and a Polish summary is available from the Public Transport Board in Krakow.[10] Figure 1 displays the location of each the ten sampling sites and the number of measurements collected at each site.

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

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



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.

For this analysis, Krakow measurements are compared with a collection of European remote sensing measurements termed the "CONOX" database. The database was funded by Switzerland's Federal Office for the Environment and brought together data collected in France, Spain, Sweden, Switzerland, the United Kingdom.[11] The latest update

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

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 et al., "Contribution of Vehicle Remote Sensing to In-Service/Real Driving Emissions Monitoring—CONOX Task 3 Report" (Federal Office for the Environment, Switzerland, May 2018), of the CONOX database was documented in the report on the Paris campaign conducted in mid-2018[12] and all measurement campaigns in the database will collectively be referred to as "CONOX".

Note that, throughout the report, blue graph elements are used for Krakow and brown for CONOX remote sensing data. All whiskers and shaded areas in graphs refer to 95% confidence intervals of the mean.

Data preparation

Methods for analyzing and aggregating remote sensing measurements have been described in previous studies. Key methods include the conversion from tailpipe pollutant concentrations to distance-specific estimates in gram per kilometer (g/km), the unit used in European light-duty vehicle regulations.[13] Estimating engine load using vehicle specific power (VSP), conventionally reported in kilowatt per ton (kW/ton), is another key method which relies on average values of aerodynamic and rolling resistance of vehicles to estimate instantaneous power demand. The method and parameters have been documented in a variety of reports.[14]

Remote sensing measurements become are most useful when basic technical characteristics such as fuel type, emission 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 emission standard was available for only 14% of vehicles and was primarily available for relatively new vehicles type-approved to Euro 6 and Euro 6d-TEMP. Because the emission 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 to all new vehicle registrations. The phase-in period typically lasts one year. The latter dates were applied to Krakow data to calculate emission standards for vehicles, furnishing a conservative estimate that, for a vehicle registered during the phase-in period, assigns the emission standard being phased out rather than the emission standard being phased

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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.

[12] Dallmann et al., "Remote Sensing of Motor Vehicle Emissions in Paris."

[13] Yoann Bernard et al., "Determination of Real-World Emissions from Passenger Vehicles Using Remote Sensing Data" (Washington, D.C.: TRUE Initiative, June 5, 2018), https://theicct.org/publications/real-world-emissions-using-remote-sensing-data.

[14] Bernard et al.; Uwe Tietge et al., "A Comparison of Light-Duty Vehicle NOx Emissions Measured by Remote Sensing in Zurich and Europe" (Washington, D.C.: Canton of Zurich Office for Waste, Water, Energy and Air, June 27, 2019), https://theicct.org/publications/LDV-comparison-NOx-emissions-Zurich.

in. To provide a sense of the uncertainty involved in estimating emission standards, Figure 2 presents the share of passenger cars by emission standard for which the value was reported, estimated, or estimated during a phase-in period. The Euro 6d-TEMP standard was never estimated as the phase-in period ended in September 2019, after the Krakow remote sensing campaign was completed.

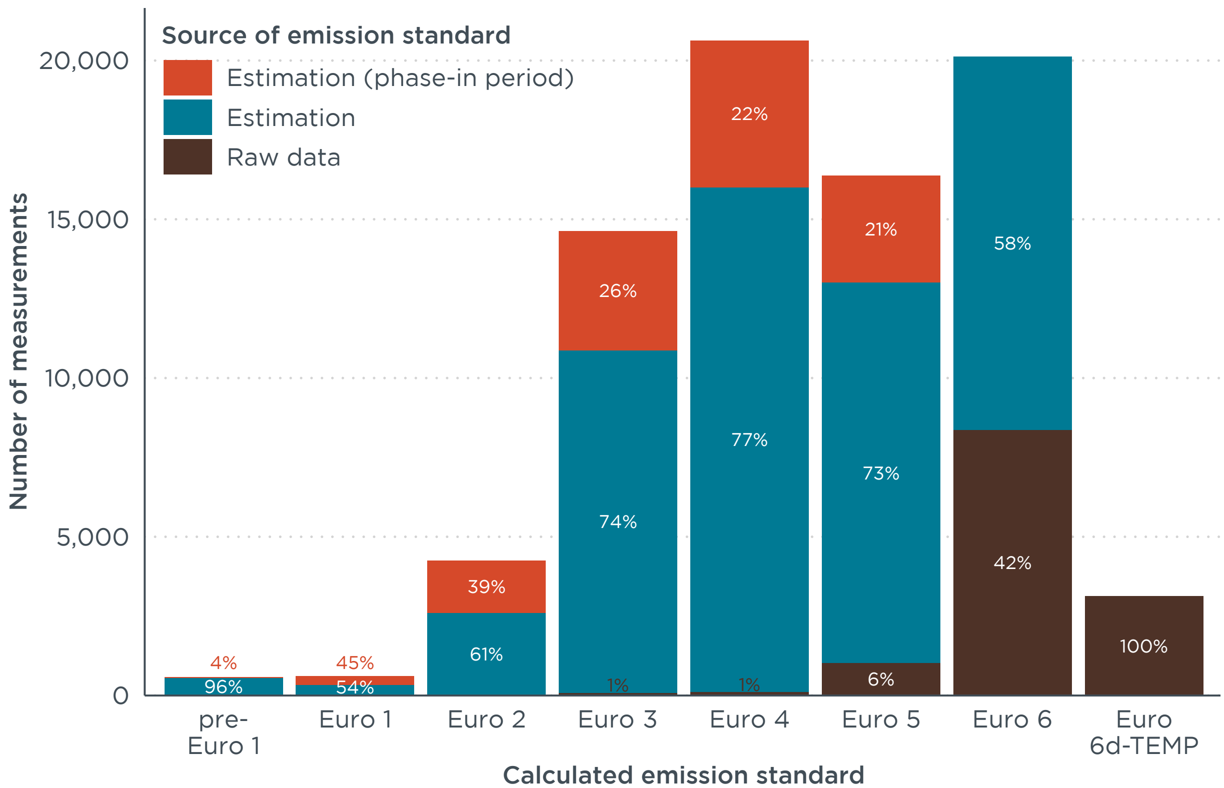

Figure 2. Source of emission standard values for passenger cars.

Sample overview

Figure 3 provides an overview of the Krakow sample by vehicle category, fuel type, and emission standard. The majority (77%) of measurements pertained to passenger cars, with light commercial vehicles (8%), and buses (1%) account 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 gasoline 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. Compared with the most recent campaign in the CONOX database, the Paris campaign of 2018, the share of older vehicles is substantially higher in 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. Approximately 4% of passenger cars in Krakow were type-approved to the current emission standard, Euro 6d-TEMP. As a result, Krakow measurements are a key data source for both aged and modern vehicles.

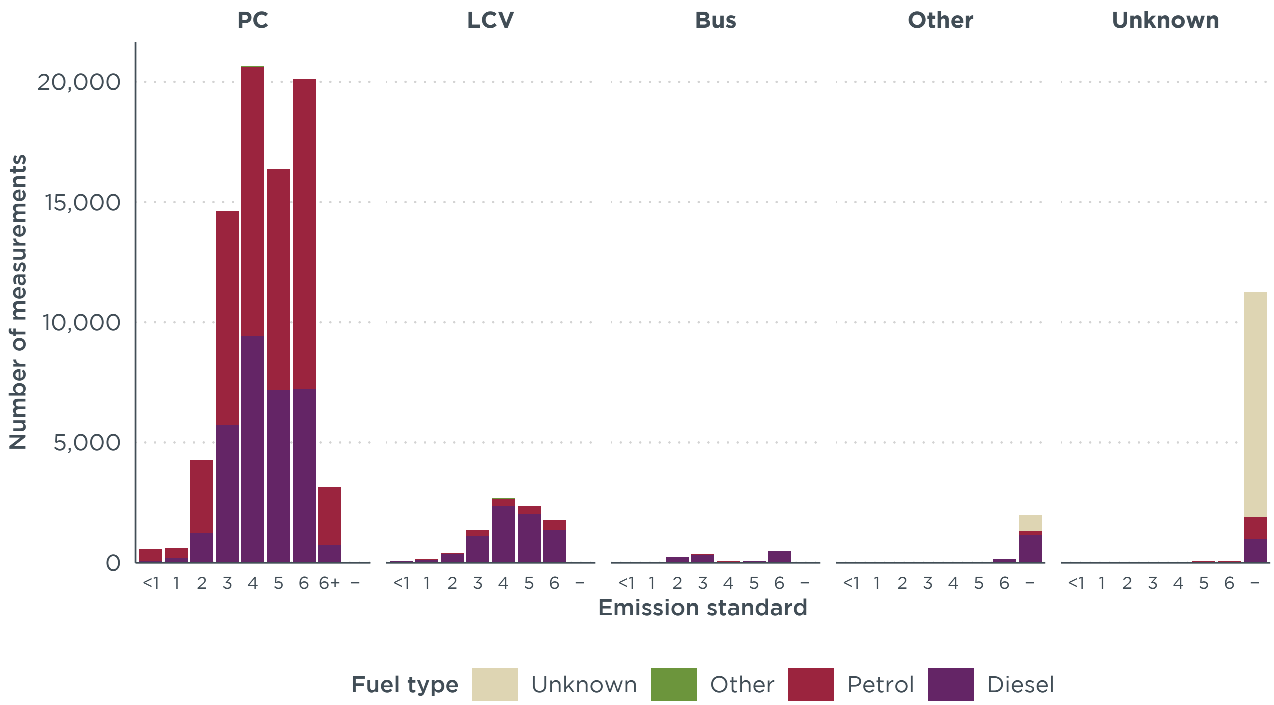

Figure 3. Number of remote sensing measurements by vehicle category, estimated emission standard, and fuel type. Euro <1 refers to vehicle predating Euro standards; 6+ refers to the Euro 6d-TEMP emission standard; en dashes (–) represent unknown values.

Table 1 provides an overview of vehicle characteristics and measurement conditions in Krakow and CONOX data. Vehicles measured in Krakow were on average two years older than 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 Euro standards 3–4, and consistently higher than CONOX median values since Euro 5. Measurement in Krakow were conducted during a heat wave, with median ambient temperatures near 30°C, exceeding Paris 2018 measurements by almost 4°C and making the 2019 Krakow measurements the hottest remote sensing campaign in the CONOX database. As per the requirements of the Krakow City Council, estimated VSP values ranged from 2 to 10 kW/ton. The median value of approximately 7 kW/ton was considerably lower than median engine load in the CONOX database and especially the high-load conditions in Zurich measurements.[15] This pattern is reflected in the average speed below 40 km/h and average acceleration below 2 km/h/s in Krakow, both consistently lower than CONOX averages.

[15] 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, NEDC)	Ambient temperature (°C)	Vehicle-specific power (kW/ton)	Acceleration (km/h/s) over speed (km/h)
				100 150 200 250	10 20 30	0 10 20	
pre-Euro 2 Diesel	258 681	25 19	2.4% 5.0%	218	21.6 28.9	7 9.2	0 2 4 6 / 20 40 60 80
pre-Euro 2 Petrol	907 5,979	33 22	2.2% 7.7%	137 194	21.8 29.9	6.8 14.6	0 2 4 6 / 20 40 60 80
Euro 2 Diesel	1,246 5,076	20 17	2.2% 3.6%	163	22.2 29.6	6.9 8.1	0 2 4 6 / 20 40 60 80
Euro 2 Petrol	3,009 20,828	20 16	2.0% 6.0%	183 232	21.5 29.4	6.8 12.3	0 2 4 6 / 20 40 60 80
Euro 3 Diesel	5,705 33,564	16 12	2.1% 3.4%	147 159	22 29.9	6.8 7.5	0 2 4 6 / 20 40 60 80
Euro 3 Petrol	8,928 43,923	16 12	2.0% 4.5%	156 172	19.7 29.7	6.8 9.3	0 2 4 6 / 20 40 60 80
Euro 4 Diesel	9,416 77,876	11 7	2.0% 3.7%	145 154	21.7 29.6	6.8 7.9	0 2 4 6 / 20 40 60 80
Euro 4 Petrol	11,212 103,094	11 9	2.0% 5.7%	153 163	20.6 29.9	6.8 12.2	0 2 4 6 / 20 40 60 80
Euro 5 Diesel	7,191 113,084	6 4	1.9% 4.1%	130 139	21.9 29.9	6.8 8.3	0 2 4 6 / 20 40 60 80
Euro 5 Petrol	9,176 84,374	6 4	1.9% 5.8%	134 139	20.7 30	6.8 12.1	0 2 4 6 / 20 40 60 80
Euro 6 Diesel	7,981 64,546	2 1	1.8% 2.9%	114 130	23 29.8	6.2 6.8	0 2 4 6 / 20 40 60 80
Euro 6 Petrol	15,251 40,691	2 2	1.9% 3.7%	118 132	22.3 29.8	6.9 7.9	0 2 4 6 / 20 40 60 80
Total	80,280 593,716	9 7	2.0% 4.5%	139 139	21.6 29.8	6.8 9.2	0 2 4 6 / 20 40 60 80

In short, the 2019 Krakow measurements campaigns stands out from the CONOX database for three reasons. First, Krakow measurements are the first campaign conducted in Eastern Europe, with other campaigns focusing on France, Spain, Sweden, Switzerland, and the United Kingdom. Second, average vehicle age was considerably higher in Krakow than in other measurements campaigns. Somewhat counterintuitively, as the most recent campaign, 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 monoxide (NO) and nitrogen dioxide (NO_2) emissions. Both pollutants were measured in this campaign. NO is not directly dangerous to humans but turns into harmful NO_2 within a few hours of contact with oxygen in the surrounding air. Therefore, it is common practice in regulations and research to report 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 average fuel-specific NO_x emissions in grams NO_x emitted per kilogram fuel burned (g/kg) from passenger cars by fuel type and emission standard, comparing levels in Krakow and CONOX. 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 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 Krakow NO_x emissions typically exceeding CONOX levels and the difference being more pronounced for early emission standards. The difference between 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[16] and petrol vehicles of early emission standards were significantly older in Krakow than in the CONOX database (see Table 1).

[16] 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.

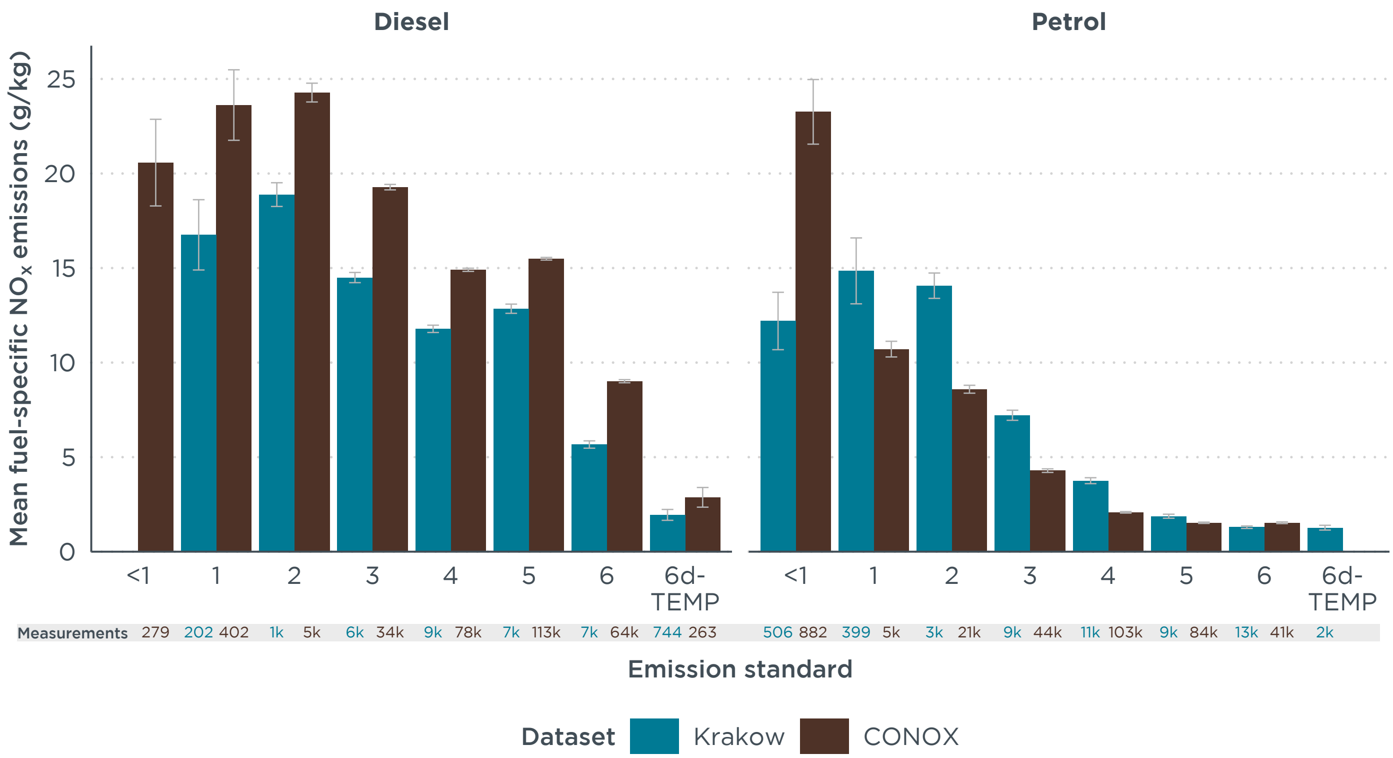

Figure 4. Mean fuel-specific NOx emissions from diesel and gasoline passenger cars, grouped by emission standard, for Krakow and CONOX remote sensing data. The number of measurements is presented below each bar. Whiskers represent the 95% confidence interval of the mean. Averages are only shown for groups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

Figure 5 investigates the differences in NO_x emissions from diesel passenger cars between Krakow and CONOX. The figure explores the relation between VSP and NO_x emissions per emission standard using generalized additive models, as implemented in the mgcv[17] and ggplot2[18] packages for the R software environment.[19] 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 for the ambient temperature range in Krakow

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[17] 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.

[18] 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.

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

measurements. Both VSP and ambient temperature have been shown to impact NO_x emissions from diesel passenger cars.[20]

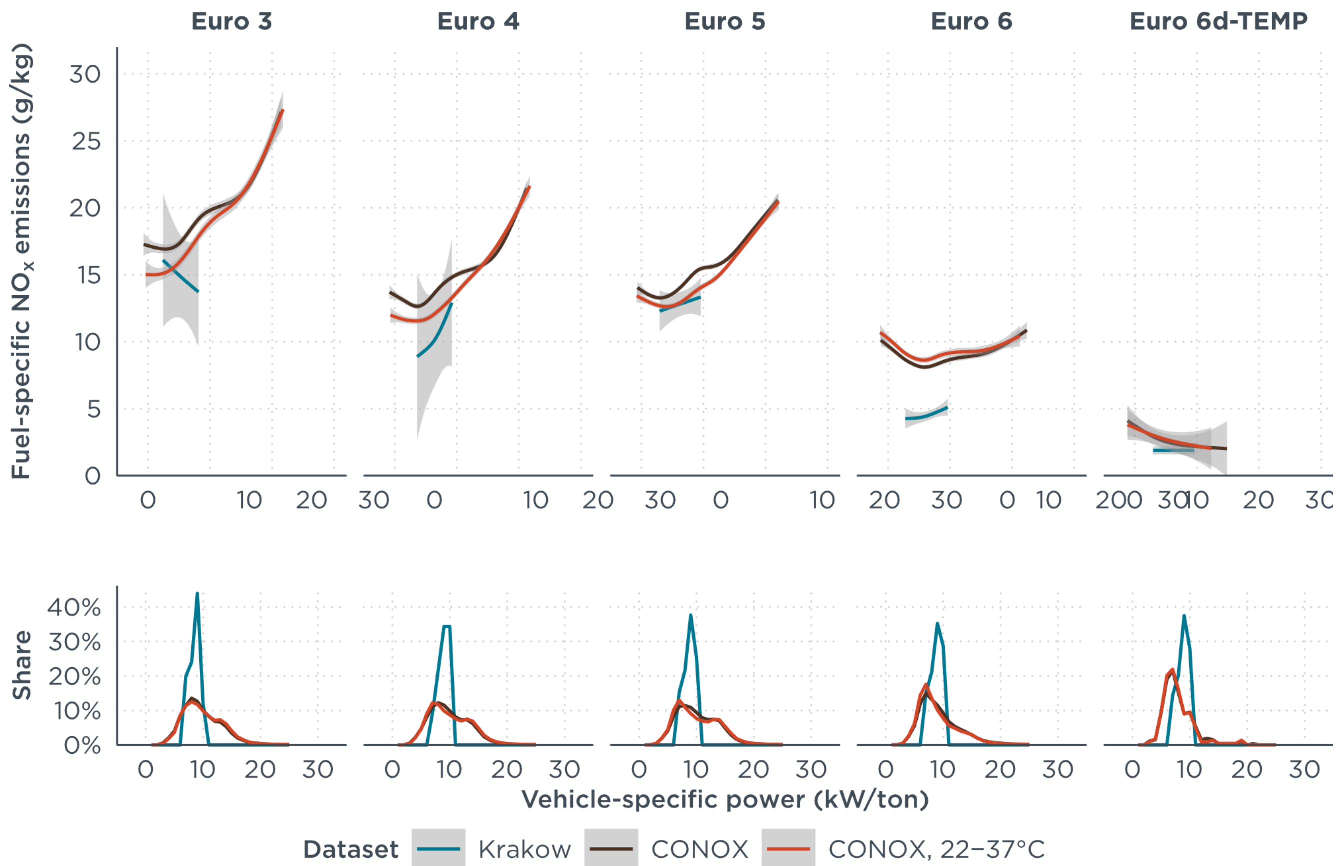

Figure 5. Top graph: Comparison of fuel-specific NO_x emissions from Euro 3 through Euro 6d-TEMP diesel passenger cars as a function of VSP in multiple remote sensing datasets: Krakow (blue), CONOX (brown), and CONOX filtered for Krakow ambient temperature range (orange). The relationship between NO_x 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).

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 helps align Krakow and CONOX averages. Euro 6 vehicles are a notable exception: Neither VSP nor ambient temperature account for the differences

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[20] 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.

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 average NO_x emissions of the Euro 6 group.

Figure 6 presents average distance-specific NO_x emissions by fuel type and emission standard in Krakow and CONOX data. Overall, trends in emission levels and differences between Krakow and CONOX results are similar to 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 diesel counterparts (up to 0.57 g/km).

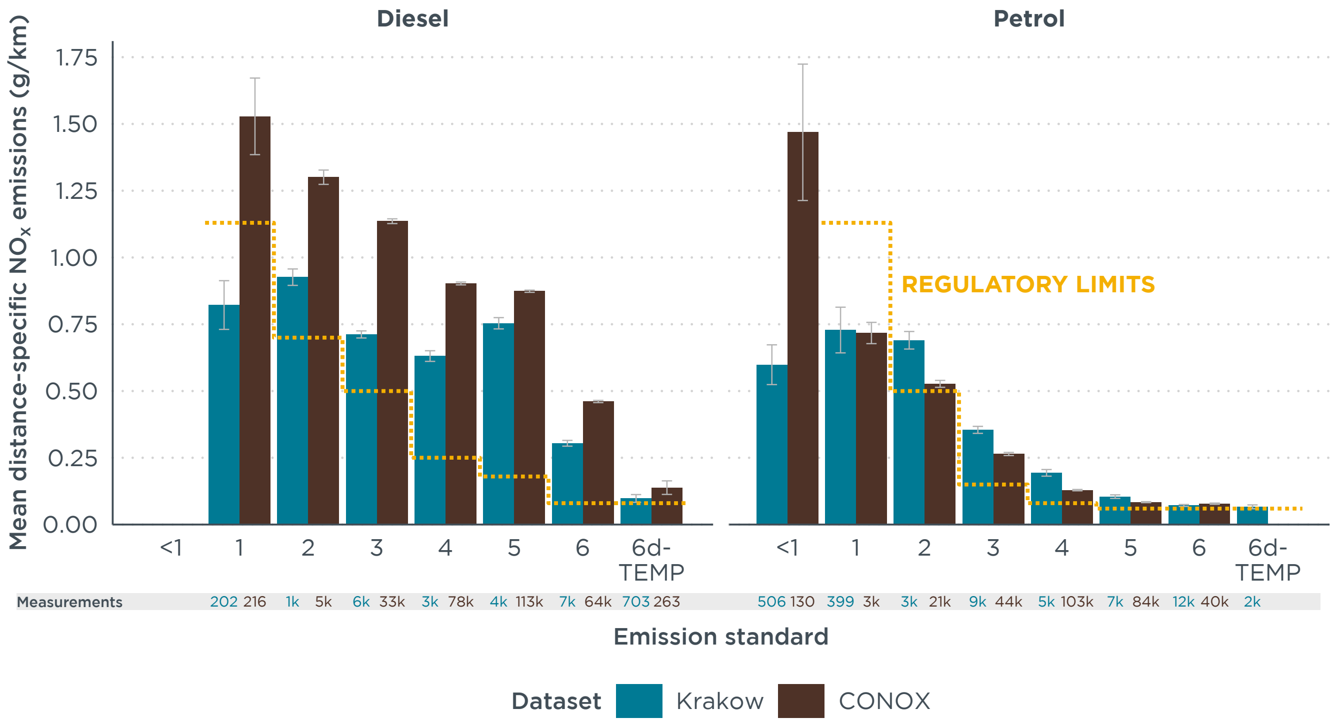

Figure 6. Mean distance-specific NO_x emissions from diesel and petrol passenger cars, grouped by emission standard, for Krakow and CONOX remote sensing data. The number of measurements is presented below each bar. Whiskers represent the 95% confidence interval of the mean. Averages are only shown for 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 focuses on Euro 6d-TEMP passenger cars and plots average distance-specific NO_x emissions by fuel type and vehicle make. On average, diesel vehicles emitted 0.033 g/km (51%) more than petrol vehicles. Virtually all makes met the not-to-exceed limit for on-road Real-Driving Emissions (RDE) 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 small sample sizes, estimates of the mean remain fairly uncertain, as witnessed by 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.

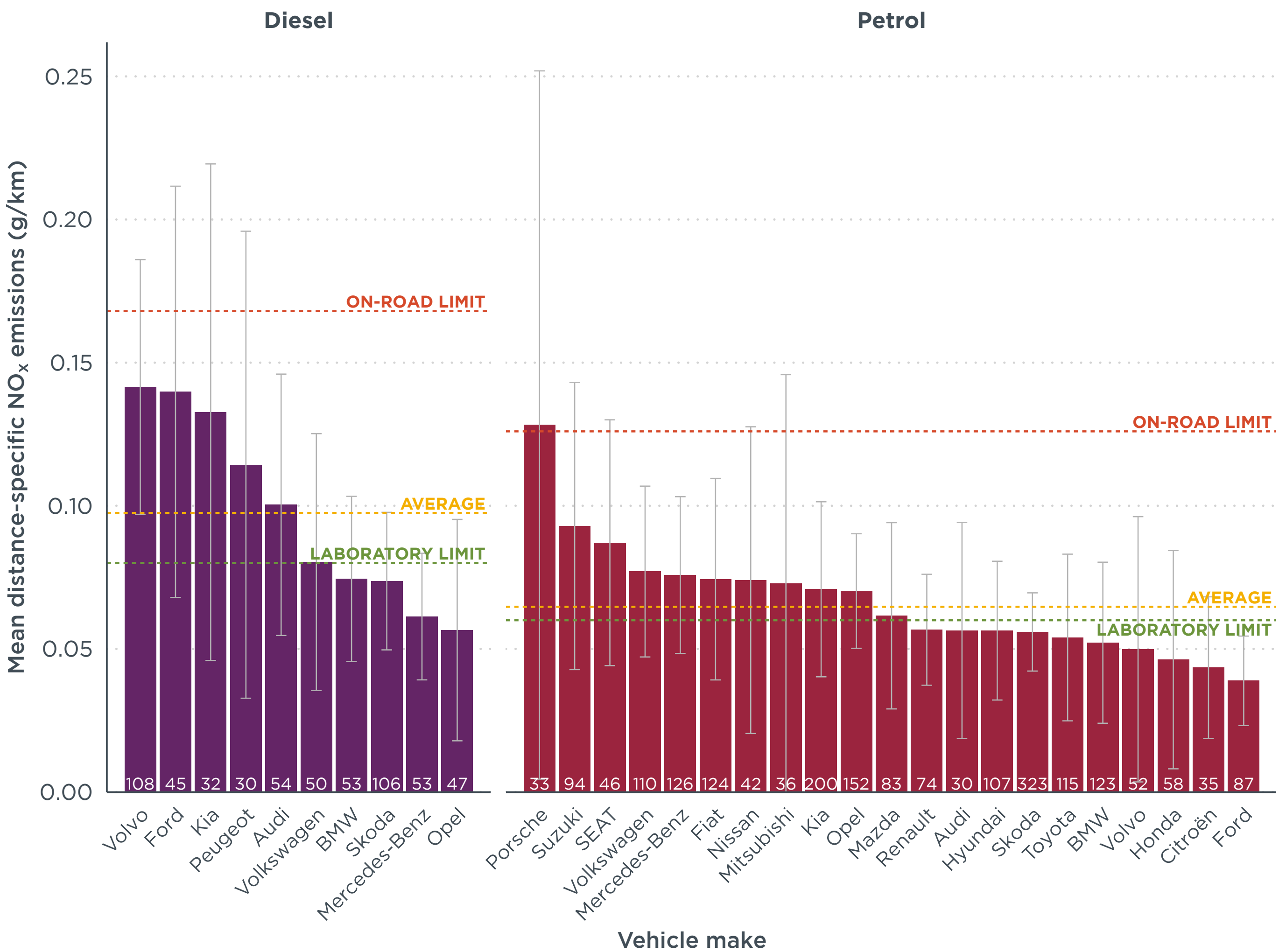

Figure 7. Mean distance-specific NO_x emissions from Euro 6d-TEMP passenger cars, grouped by fuel type and make, for Krakow and CONOX remote sensing data. The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean. Averages are only shown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

Figure 8 plots the estimated share of NO_x emissions from passenger cars over the share of measurements by fuel type and emission standard. The figure thus uses the share of remote sensing measurements as a crude proxy of vehicle-kilometers travelled by each group of vehicles. Most groups of diesel passenger cars and petrol cars predating the Euro 4 standard have a higher share of NO_x emissions than of measurements. Euro 3 diesel passenger cars have the highest share of NO_x emissions, approximately 20%, but account for only 7% of measurements. Diesel vehicles represent 40% of measurements and accounted for approximately 60% 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—the 2018 Paris campaign, for instance—due to the higher share of pre-Euro 4 petrol passenger cars in Krakow.

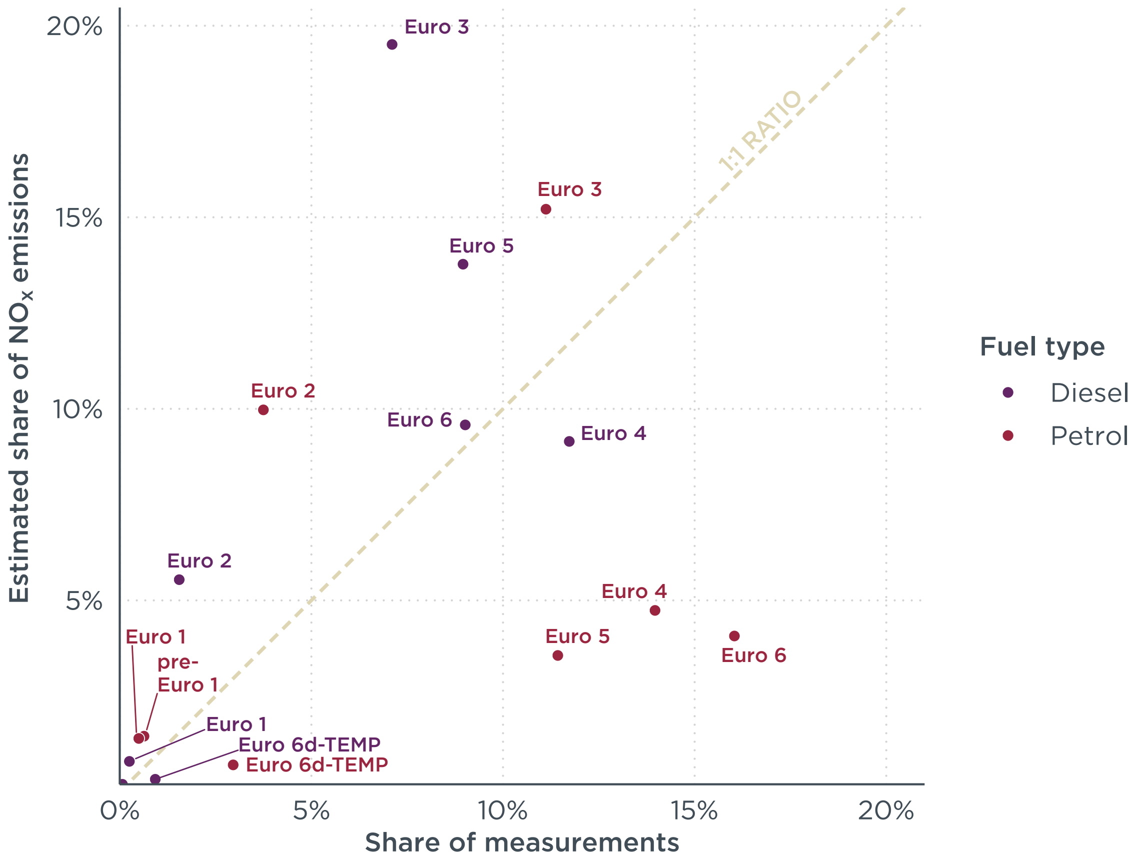

Figure 8. Estimated share of total NO_x emissions from passenger cars by Euro standard and fuel type.

Figure 9 presents average fuel-specific NO_x emissions from light commercial vehicles by fuel type and emission standard, comparing levels in Krakow and CONOX. Emission levels and trends over time are similar to passenger car results presented in Figure 4: Diesel emissions levels were relatively unaffected by Euro standards 1–5 while petrol NOx emissions declined. Results for petrol vehicles are sparse because the vast majority of light commercial vehicles are diesel-fueled.[21] Similar to passenger car results, diesel NO_x emissions were lower and petrol NO_x emissions higher in Krakow than in CONOX. Explanations for the differences are expected to be 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 were thus not

[21] Georg Bieker et al., "European Vehicle Market Statistics, 2019/2020" (Washington, D.C.: International Council on Clean Transportation, December 16, 2019), https://theicct.org/publications/european-vehicle-market-statistics-20192020.

shown in the figure. The emission standard is being phased-in from September 2018 to September 2020 for light commercial vehicles, one year later than for passenger cars.

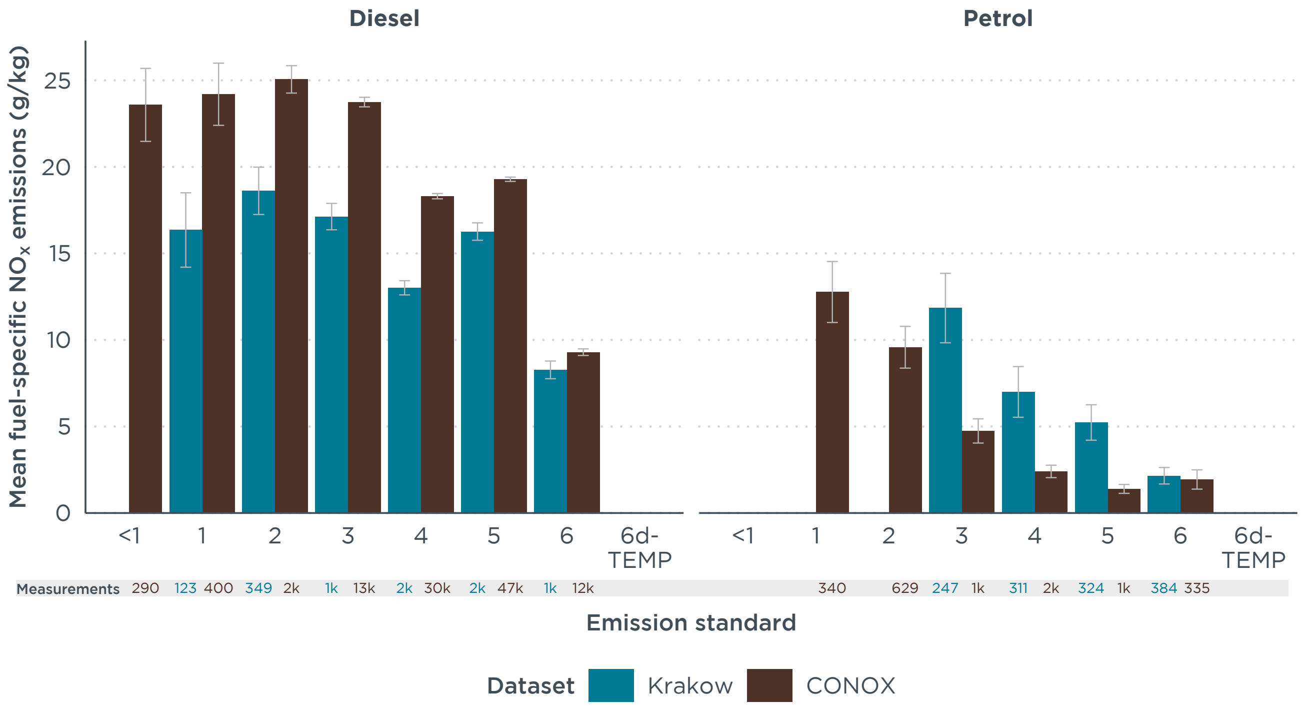

Figure 9. Mean fuel-specific NO_x emissions from diesel and petrol light commercial vehicles, grouped by emission standard, for Krakow and CONOX remote sensing data. The number of measurements is presented below each bar. Whiskers represent the 95% confidence interval of the mean. Averages are only shown 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. Results are grouped by fuel type and emission standard and compare emission levels in Krakow and CONOX. As in previous remote sensing campaigns, CO emissions from petrol vehicles in Krakow decreased with emission standards while emissions from diesel vehicles historically have been comparatively low. Average CO emissions from Euro 6 petrol passenger cars came within 23% of 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 notably 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.[22]

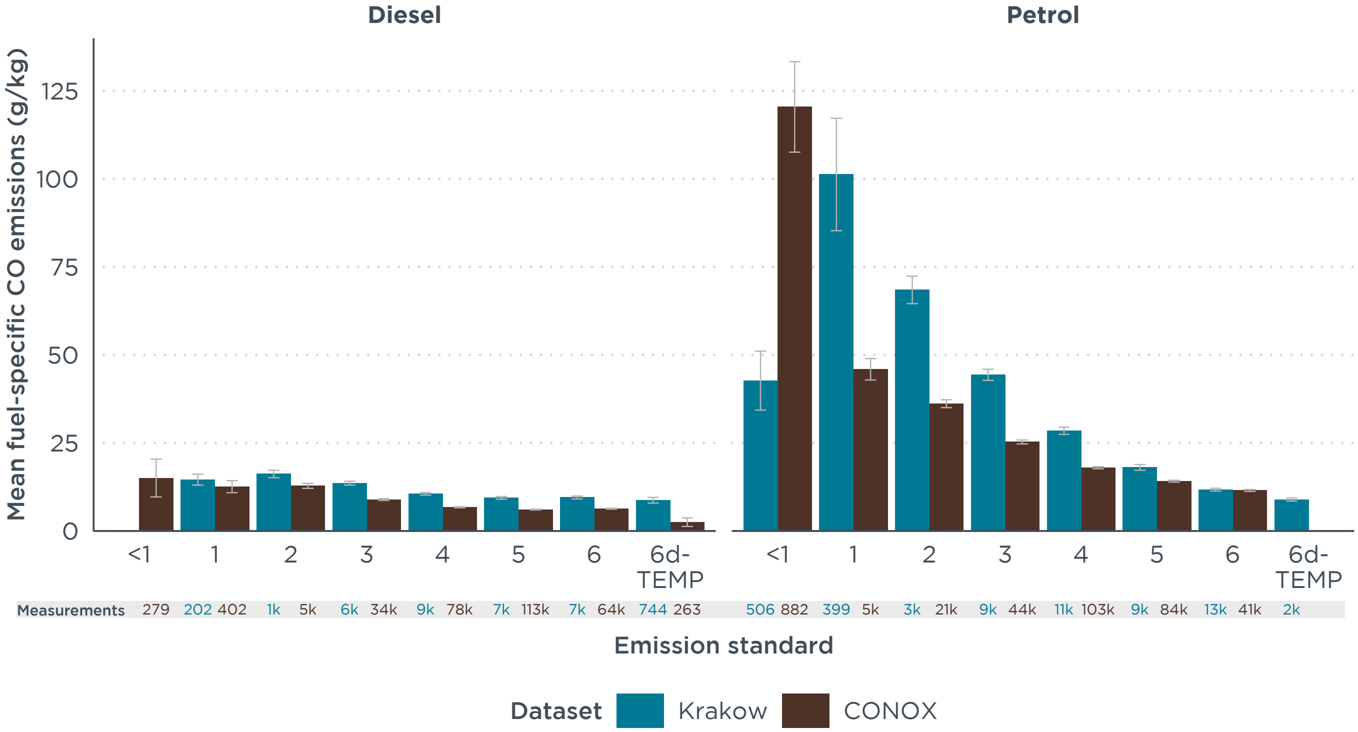

Figure 10. Mean fuel-specific CO emissions from diesel and petrol passenger cars, grouped by Euro standard, for Krakow and CONOX remote sensing data. The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean. Averages are only shown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

[22] 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."

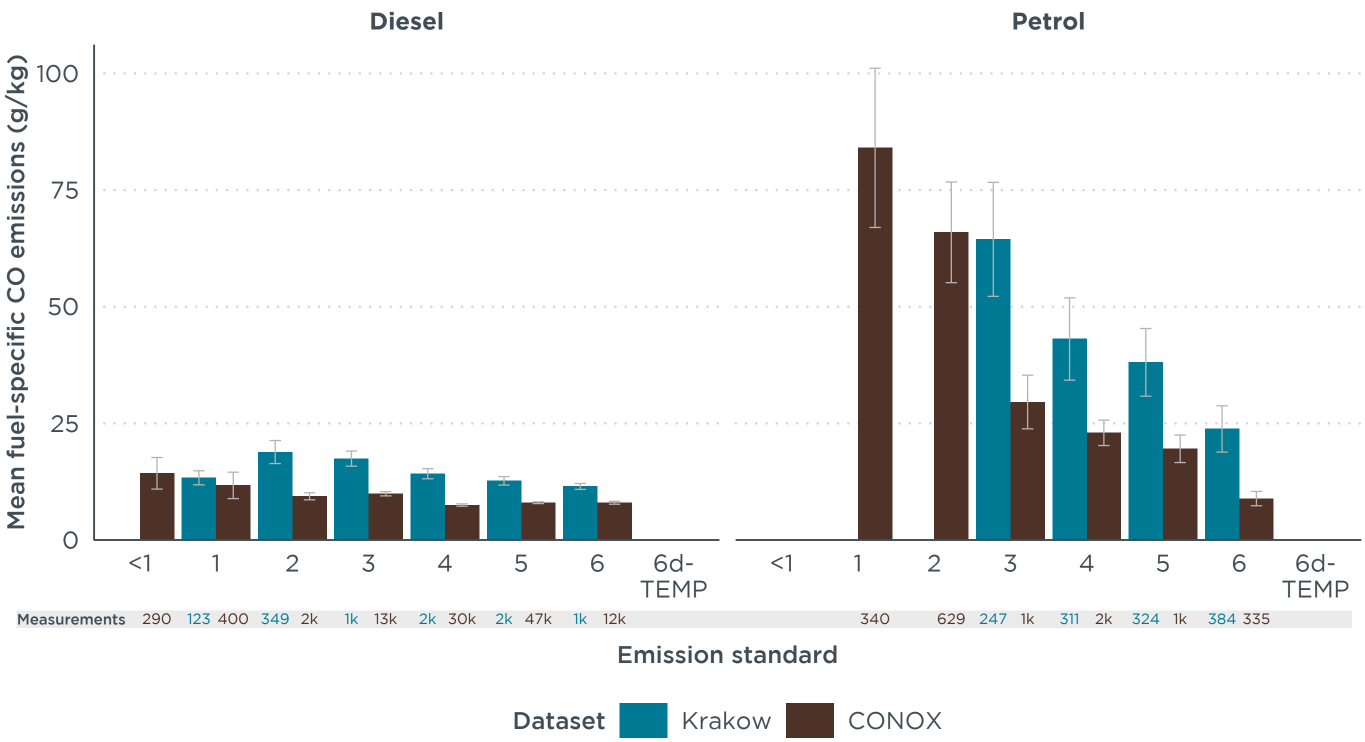

Figure 11. Mean fuel-specific CO emissions from diesel and petrol light commercial vehicles, grouped by Euro standard, for Krakow and CONOX remote sensing data. The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean. Averages are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

Light-duty vehicle particulate matter emissions

The RSD5000 remote sensing instrument used in the Krakow campaign measures exhaust plume opacity as a proxy for particulate matter (PM) emissions. The opacity measurement gives 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.

Figure 12 and Figure 13 show average PM emissions from passenger cars and light commercial vehicles, respectively. Results are grouped by fuel type and emission 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 Paris measurements were collected using the Hager Environmental & Atmospheric Technologies (HEAT) Emissions Detection and Reporting (EDAR) instrument[23], and results are not directly comparable with Opus RSD5000 measurements.[24] In Krakow as in CONOX, PM emissions from diesel Euro 5 and Euro 6 vehicles 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. Krakow emission levels were consistently lower than CONOX averages.

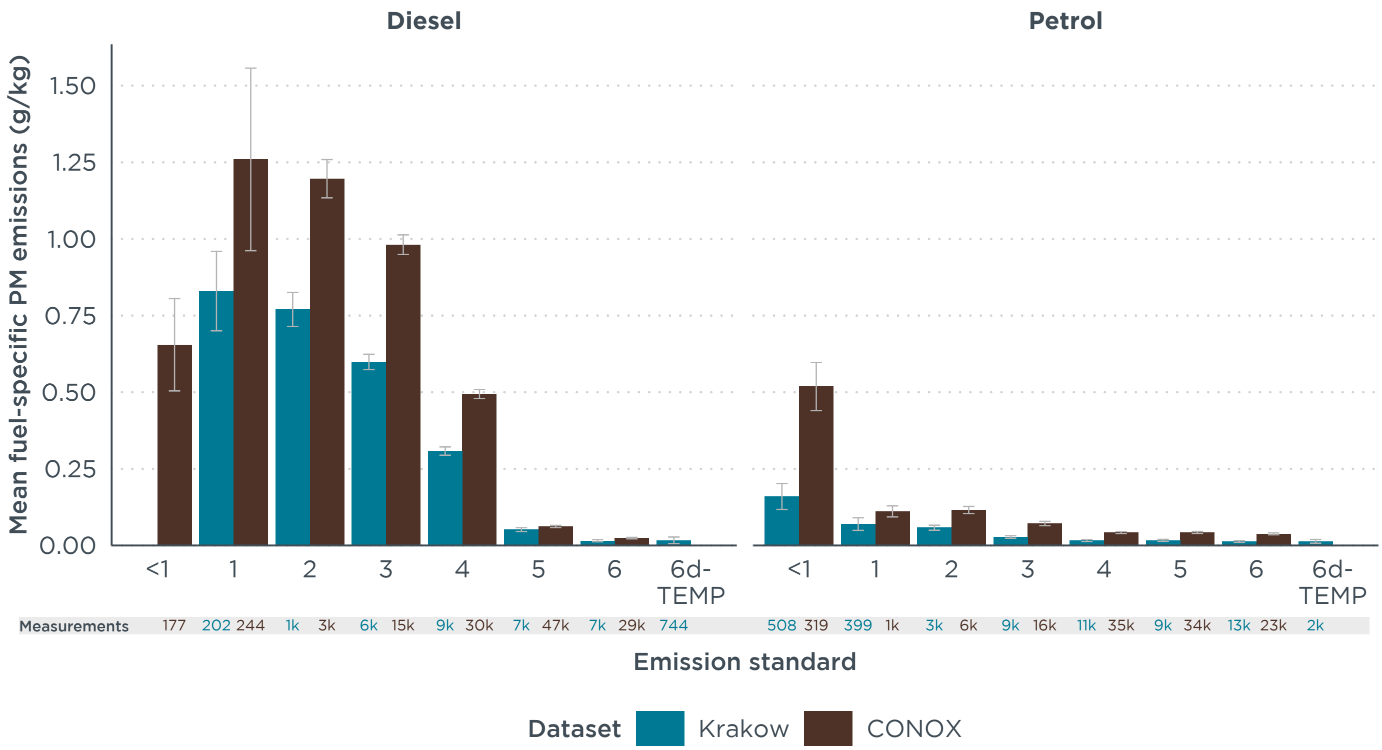

Figure 12. Mean fuel-specific PM emissions from diesel and petrol passenger cars, grouped by Euro standard, for Krakow and CONOX remote sensing data. The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean. Averages are only shown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

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[23] 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.

[24] Dallmann et al., "Remote Sensing of Motor Vehicle Emissions in Paris."

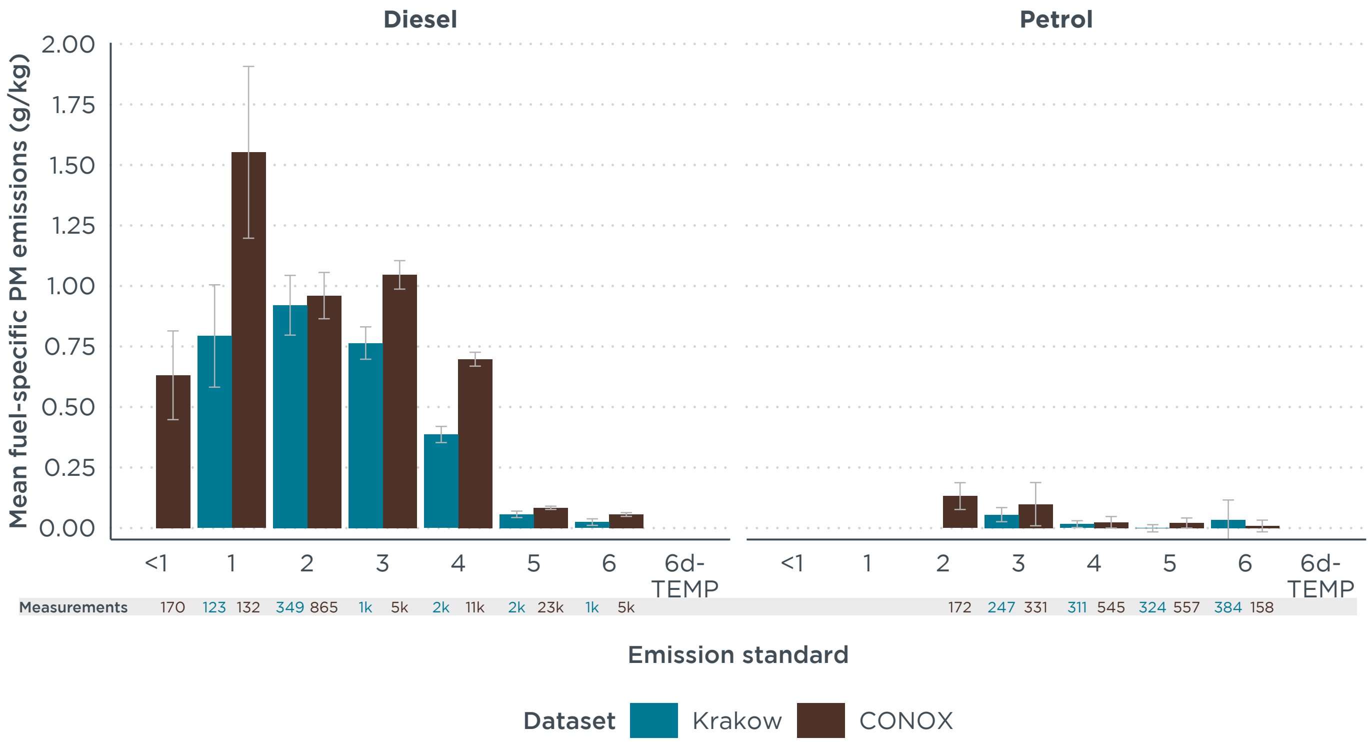

Figure 13. Mean fuel-specific PM emissions from diesel and petrol light commercial vehicles, grouped by Euro standard, for Krakow and CONOX remote sensing data. The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean. Averages are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

Figure 14 investigates the differences in PM emissions from diesel passenger cars between Krakow and CONOX. The figure explores the relation between VSP and PM emissions per emission standard using generalized additive models. VSP ranges are truncated, from the 5th to 95th percentile per group, to avoid plotting relationships for ranges with scarce data. For Euro 5–6 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 DPF. 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. That behavior appears consistent with the lean – that is with excess air – diesel-type of combustion that typically requests 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 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.

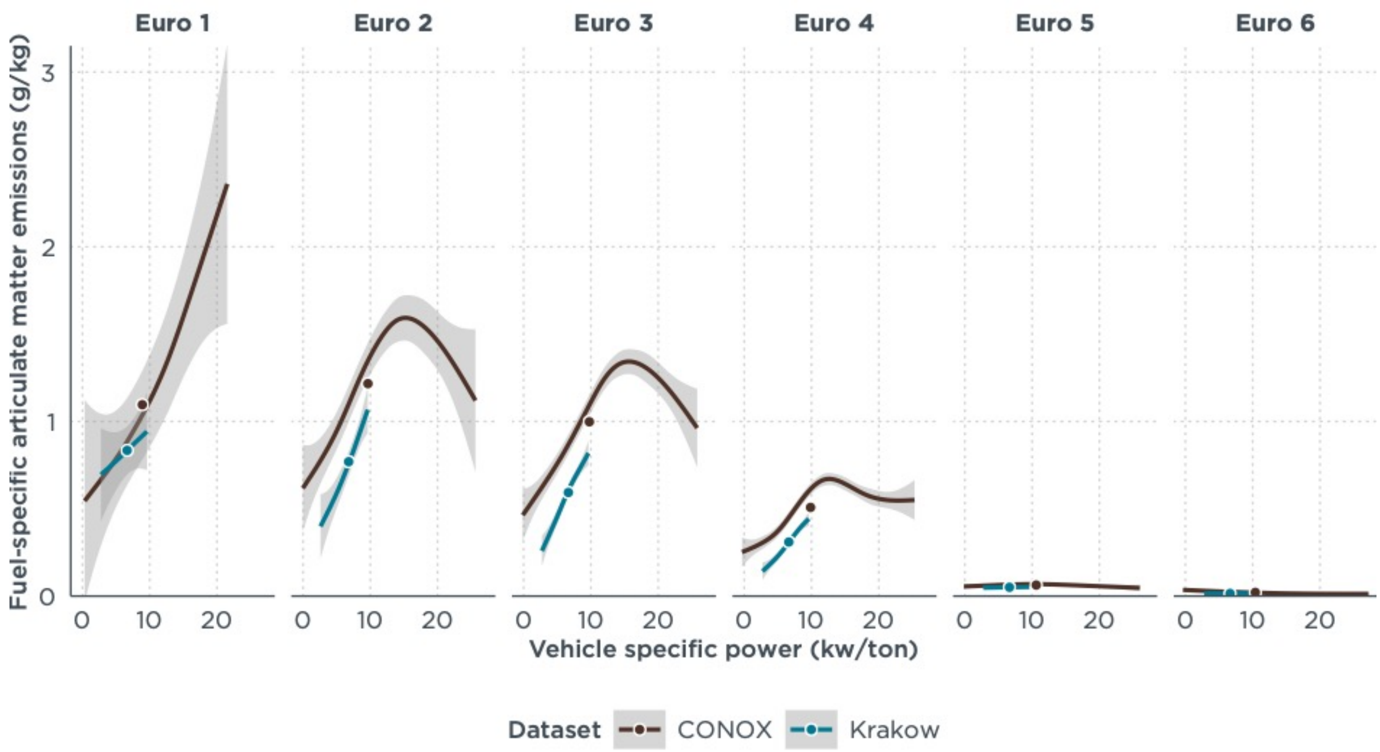

Figure 14. Comparison of fuel-specific PM emissions from Euro 1 through Euro 6 diesel passenger cars as a function of VSP in Krakow (blue) and CONOX (brown). The relationship between PM emissions and VSP is represented using generalized additive models with 95% confidence intervals. Round markers represent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

Case study: Taxis

This case study examines the remote measurements of the fleet of taxis 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, passenger car measurements.

Figure 15 compares the taxi fleet composition in terms of fuel type and emission 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. 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 also 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 cars are significantly more common as taxis than they are passenger cars.

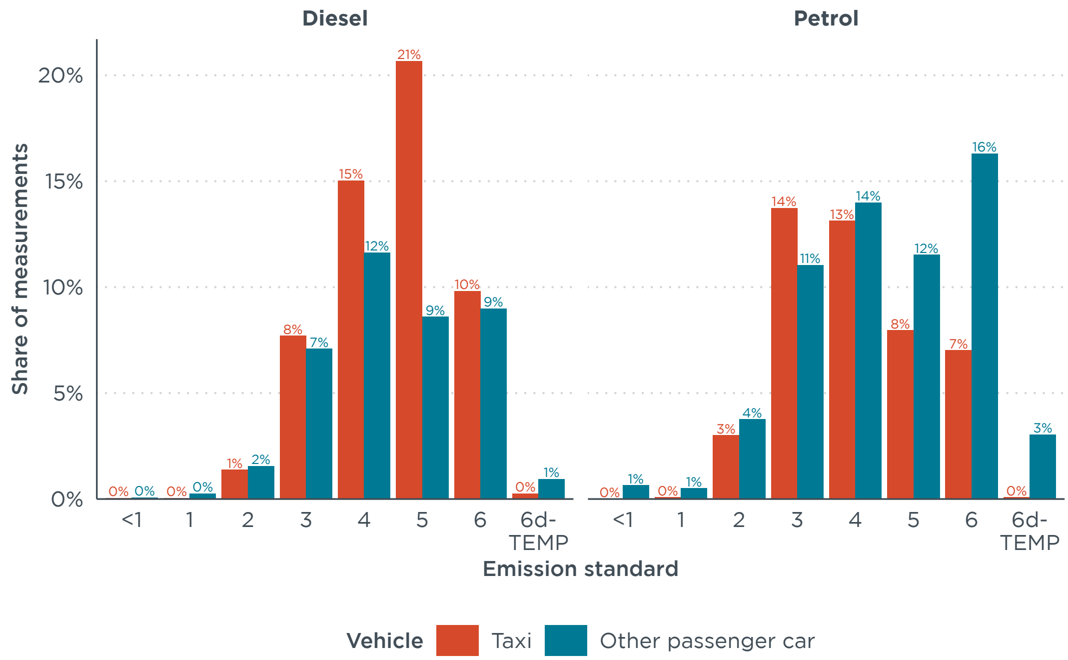

Figure 15. Comparison of Krakow taxi and other passenger car fleet composition in terms of fuel type and emission standard.

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 are 59% higher than from passenger cars, and are higher across all fuel type and emission standard combinations except diesel Euro 2 and 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 petrol NO_x emission levels, particularly in vehicles type-approved to older emission standards.[25] Pre-Euro 6 diesel vehicles do not rely so heavily on these devices to reduce NO_x emissions (which tend to degrade consistently over time) and 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, and it is likely that the dominance of certain brands in the taxi fleet had an impact on these figures. In particular, 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

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

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, petrol taxis are a minority of the taxi fleet, but as with NO_x emissions, the mileage-related degradation of exhaust aftertreatment systems means that they generally emit more CO than other passenger cars. Fleet-wide PM emissions are close to the detection limit of remote sensing instruments.

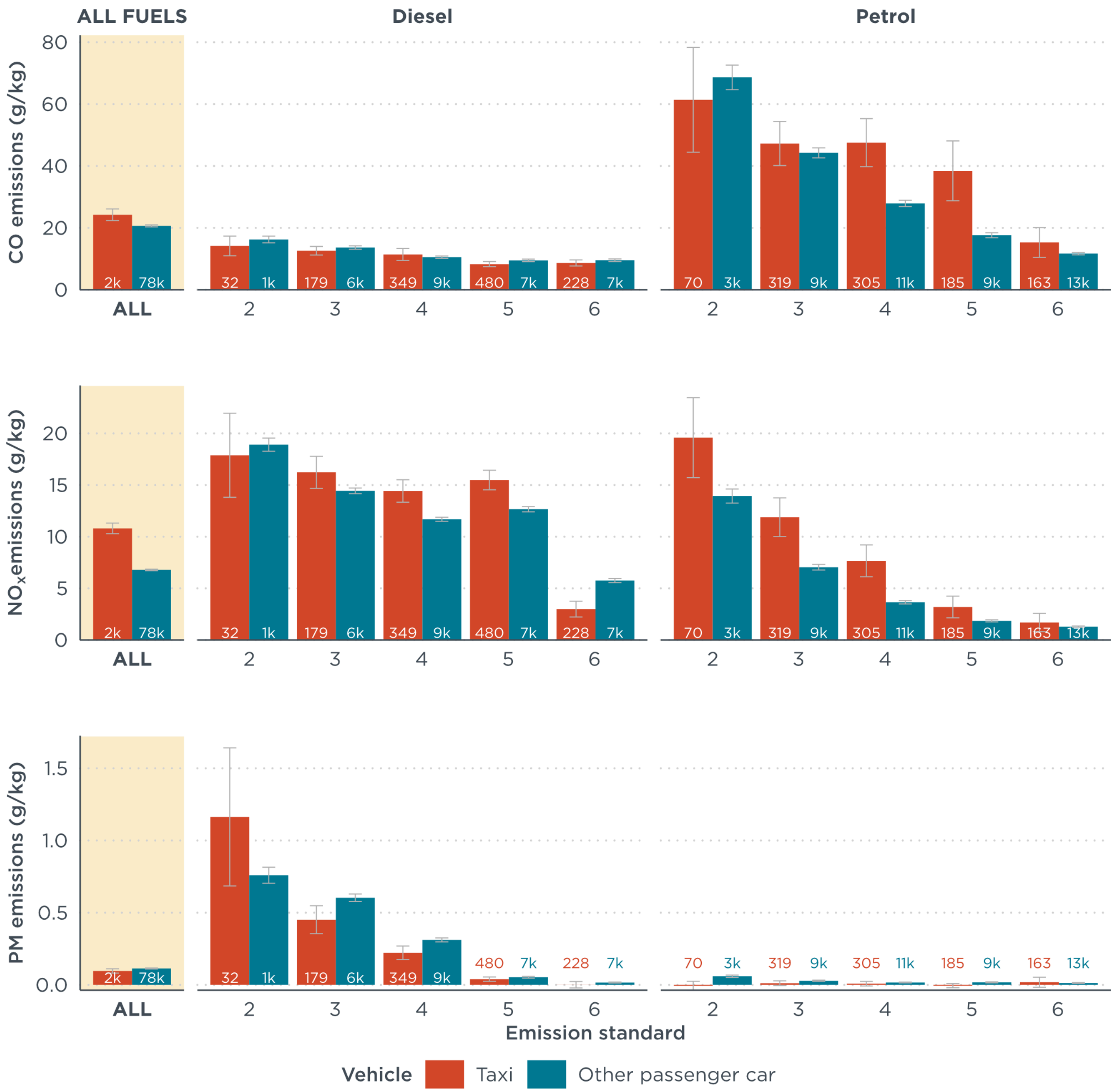

Figure 16. Mean fuel-specific CO, NO_x, and PM emissions from Krakow taxis and other passenger cars in total and by fuel type and emission standard. The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean.

Case study: Buses

The following section focuses on Krakow's fleet of urban passenger bus services. The city has a mixed portfolio, comprising both state-run municipal services and privately-managed commercial operators. This latter category is split into two types - those which are listed on the central registry and those which are not.

Figure 17 illustrates the range of both operator and vehicle types. In terms of data sources, the Krakow transport authority maintains a central vehicle registry for the majority of operators, however this is not exhaustive as many operators are not listed on this database. These have been recorded separately within the dataset under "others", and for the sake of this study we will refer to them as "unlisted". To be clear, this does not imply that the vehicles or companies are generally unregistered or unauthorized in any sense, but merely that they are not part of Krakow transport authority's central register.

Fleet profile:

We have grouped the various models into primary categories which are segmented according to body-type; namely, coaches, municipal transport buses, and van-based minibuses. The latter is typically limited to passenger counts of between 10-20 and are either type-approved to LDV *or* HDV emission standards according to vehicle weight. In terms of the overall spread, this class emerges as the primary type of bus service which could seem to indicate a potential gap in public-sector service provision.

Data on emission standards has been taken from a variety of sources including the Krakow transport authority records as well as the national vehicle database. Where data is not available from these sources, the Euro engine class has been estimated based on vehicle registry date. This mainly applies to those vehicles termed as "unlisted".

Euro Classification:

In terms of Euro standards, the mass-transit municipal bus services are operated by the local authority which, as a large single entity, means the update-regime will be broadly aligned and implemented in cycles which could partially explain why the vehicles show consistent age and near universal Euro VI compliance. It is also possible to assume that public services are subject to specific regulatory measures which, compared with the private sector, might push for systematic adoption of newer vehicles that meet the latest environmental standards.

By contrast, the small-scale minibus segment falls across a range of privately-run providers and predictably displays greater variance. The majority of vehicles fall within the Euro 3/III category with Euro 6/VI and 2/II taking second and third place in the rankings. It is interesting to see that this comparatively fragmented sector shows greater polarization of vehicle ages as it would be fair to expect a normal or lightly skewed distribution. This could point to success of Euro 6/VI regulation and/or various legislative and micro-economic factors affecting vehicle choice in the private sector.

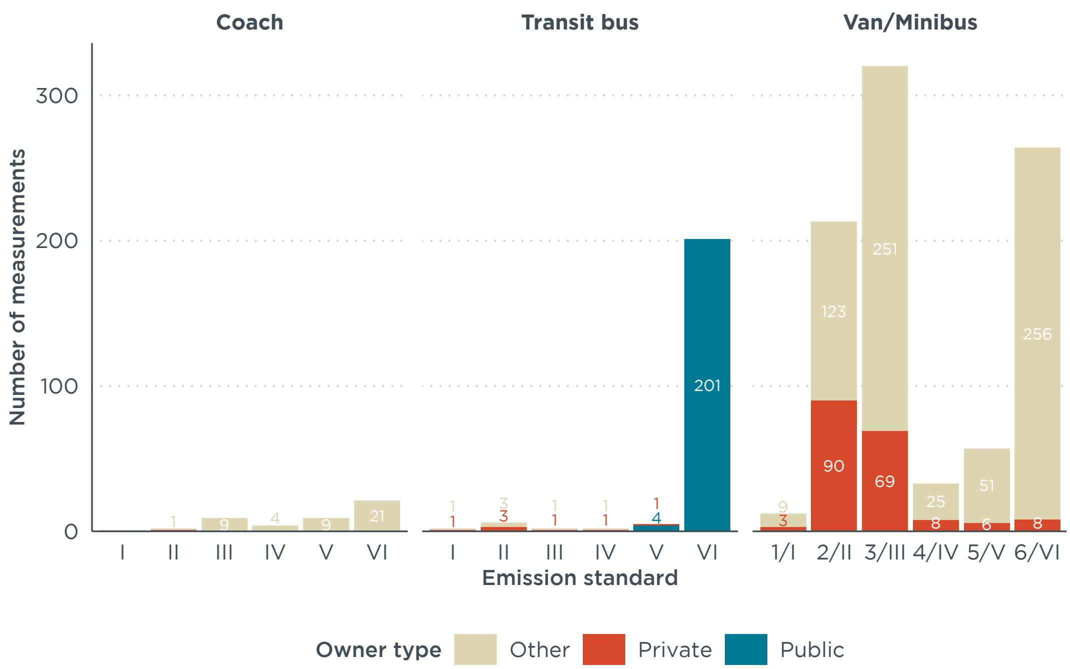

Figure 17. Number of bus measurements by emission standard and owner type.

Emissions breakdown:

When examining the composition of Krakow's bus emissions, we can immediately see some visible trends within the data.

Figure 18 illustrates readings for both Nitrogen Oxide (NOx) and Particulate Matter (PM). The data is presented according to the same owner/operator categories shown in Figure 17 and, as with other types of vehicle, there are some predictable correlations between Euro classification and the level of pollutants produced.

The most obvious distinction is the remarkably low figure attributable to public bus services. Of the 1,161 total measurements, 205 (17.6%) were municipal bus services almost exclusively employs modern Euro 6 engines. These are exhibiting the lowest to fuel-specific NO_x and PM output (displayed in blue). We don't know real-world fuel consumption of the vehicles in this study so we cannot comment on the pollutant emissions for a given distance driven, however these figures do point towards the general efficacy of Euro 6/VI measures in delivering substantially cleaner emissions as compared with previous generations. Having said that, there are some distinctions that we will examine in due course.

In contrast to the figures for Euro 6/VI, we can also see correlations between older engine classes and higher NO_x/PM outputs. Unsurprisingly, vehicles belonging to Euro 2/II and 3/III exhibit the highest NO_x and PM emission levels. The level of NO_x rises progressively with each previous Euro category but, interestingly, the levels of PM are showing incremental rises between Euro 2 and 3, as well as a stagnation of expected reductions between Euro 4 and 5.

What clearly stands out is the overall g/kg level of NO_x and PM emissions attributable to buses owned by both registered and unlisted ("other") private operators which operate exclusively in the minibus category. The data shows us that 551 (or 48%) of all buses sampled belong to Euro 2/II and 3/III exhibiting the highest emission levels. Again, we do not have sufficient vehicle or passenger data to accurately determine whether this highlights a cause for concern, however there is a correlation between the minibus fleet and average age/Euro-type which may warrant further investigation and could indicate potential for improvement.

Euro 6/VI:

As part of the analysis, we can consider the impact of Euro 6 classification in particular. Out of the 1,161 total samples taken, 465 (or 40%) come under Euro 6 designation, which is not an inconsequential figure. Breaking this down, we can see that 201 (or 43%) of this total are composed of the large-scale municipal services as compared with 264 (57%) of private-sector minibuses (both registered and other/unlisted).

We do not have data for exact body types (e.g. single/double deck, bendy-buses, and/or specific passenger numbers) but as generally larger vehicles, we could potentially assume that the passenger volumes for public-sector services tend, on average, to be somewhat higher per-vehicle than with the small-scale private operators. Further investigation would be needed to form additional findings on this point as there are many variables which could exert an influence including individual vehicle's fuel-consumption, geographic location of specific routes (e.g. near commercial or residential centers), passenger/population demographics, time of samples (day/week) etc. These factors could indeed be the reason why the smaller minibus services have evolved and could justify their method.

Nitrogen oxide:

From this standpoint we can nevertheless see that within the Euro 6 category, the -public sector services (which make up 44% of buses in this emissions class) emits much lower emissions NO_x emissions per unit of fuel burnt, as compared with the unlisted private sector services. It is widely accepted that Euro VI heavy-duty (HDV) regulations were more successful than their LDV equivalents which could partially explain the differences seen in these figures.[26] Again, further data would be needed to form any determinations.

Particulate Matter:

Euro 4/IV and 5/V generations saw an increase of regulation targeting PM emissions and this can be observed in the figures from this study, with a major drop across generations 4/IV and 5/V compared with 2/II and 3/III. There is another visible drop with the advent of Euro VI because this was the era in which diesel particulate filters (DPF) effectively became industry-standard for HDVs via regulation that sought to reduce overall particulate mass as well as limiting environmental particulate number.[27]

465 (40%) of the 1,161 total vehicle measurements in this study are from Euro VI vehicles while the graph also indicates that the amount of NO_x and PM emitted by these vehicles is minimal compared to the older Euro classes.

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[26] 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" (Washington, D.C.: International Council on Clean Transportation, January 5, 2017), https://theicct.org/publications/nox-emissions-heavy-duty-and-light-duty-diesel-vehicles-eu-comparison-real-world.

[27] Tim Dallmann and Lingzhi Jin, "Fuel Efficiency and Climate Impacts of Soot-Free Heavy-Duty Diesel Engines" (Washington, D.C.: International Council on Clean Transportation, June 3, 2020), https://theicct.org/publications/soot-free-hd-diesel-engines-jun2020.

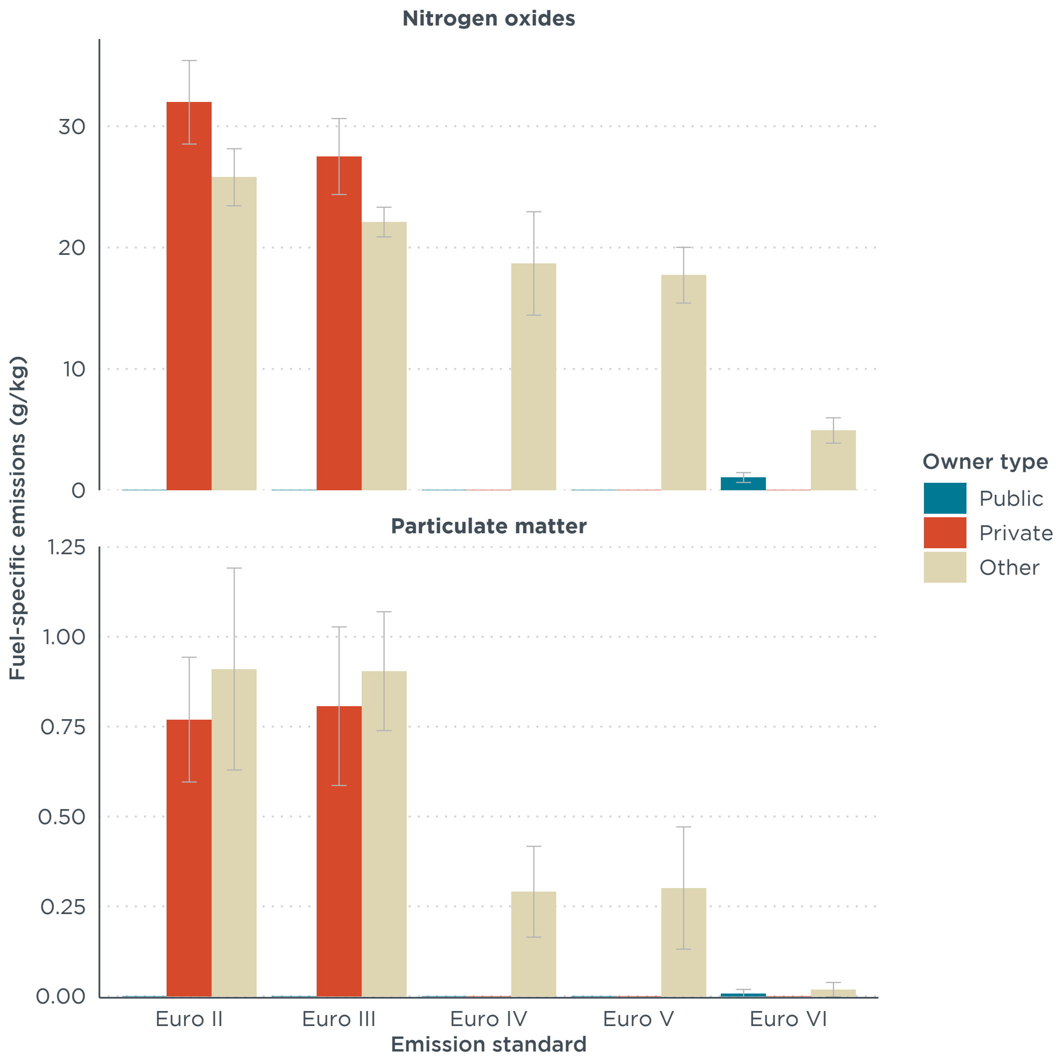

Figure 18. Fuel-specific NO and PM emissions of public, private, and other buses by emission standard. Averages are only shown for groups with at least 30 measurements.

Case study: Diesel PM high-emitters

This section studies individual PM measurements of diesel passenger cars and focuses on the highest emitting fraction.

As discussed previously in the report, 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 removal of the DPF in post-Euro 4 vehicles may lead to highly emitting vehicles that should ordinarily emit little PM. 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 emission from Euro 2 to Euro 6d-TEMP diesel passenger cars in Krakow. The fact that the distributions of successive emission standard barely overlap leaves no doubt that newer vehicles provide an overall decrease in PM emissions. In particular, Euro 5 and Euro 6 PM measurement clearly outperform pre-Euro 5 cars.

The right panel of the figure zooms in on the 95^{th} to 100^{th} percentiles, which corresponds to the 5% highest PM values by emission standard. PM emission levels remain relatively flat up to the 99^{th} percentile for Euro 5 and 99.9^{th} 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.

We find that only a small fraction Euro 5 and 6 passenger car measurements present PM levels comparable to vehicles typically not equipped with a DPF. This observation does not suggest that DPF malfunction or tampering does not occur, but that it is not unlikely to be a widespread issue leading to excess of particulate emissions in Krakow. Rather than suffering from outright failure or tampering, some DPFs may experience to 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 likely not be able to detect.

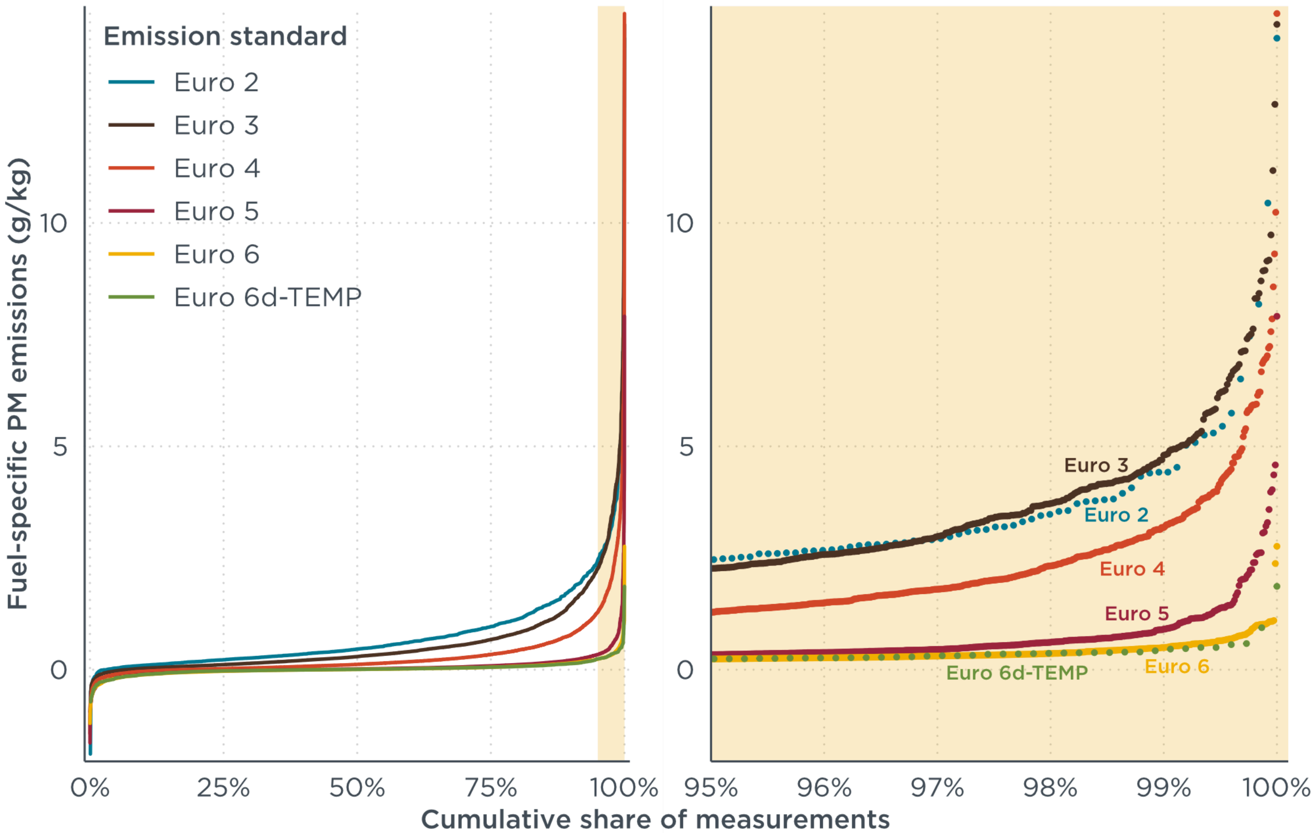

Figure 19. Cumulative distribution of diesel passenger car fuel-specific PM emissions by emission standard. Left panel: Full range. Right panel: 95th to 100th percentile.

Conclusion

The 2019 Krakow remote sensing campaign is unique in multiple aspects, not least in being the first emissions measurement program of its kind in Poland, a country where vehicle age is among the highest in Europe. This unusual context is partly reflected in the city's comparatively high overall vehicle age, although the figure is actually lower than the national average.

Beyond fleet age, the Krakow campaigns were also conducted after the introduction of Euro 6d-TEMP standards, and thus provided a rare opportunity to gather much-needed empirical data on the latest emissions regulation. Finally, the test conditions themselves were also abnormal, with the warmest ambient temperature among all CONOX campaigns and consequently lower-than-average engine loads, with a discernible impact on results.

Nitrogen Oxide

Overall, we found that NO_x emissions from diesel passenger cars measured in Krakow were lower than in other European cities. This difference was explained by favorable ambient temperatures and comparatively low engine load conditions. NO_x emissions from older petrol vehicles were generally somewhat higher than in other datasets, a finding likely explained by the older fleet in Krakow. Apart from this, 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. 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. The estimation of the share of total NO_x emissions from passenger cars by fuel type and emission standard suggests that the highest contributors are diesel vehicles and petrol cars predating the Euro 4 standard.

Carbon Monoxide

Similar to findings from previous campaigns in London and Paris, the tendency of CO emissions from light-duty petrol vehicles is to 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 a further development, 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.

Particulate Matter

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 averages from other campaigns, a phenomenon which is partially explained by the test conditions favoring lower engine load.

Taxis

As part of this investigation, a separate case study focusing on taxi emissions measured in the city of Krakow was undertaken. Overall, taxis tended to be slightly older than for passenger cars, while showing a general bias towards diesel. In particular, taxis display a higher share of diesel Euro 5 (+12 % points) models, and a lower share of petrol Euro 6 (- 9 % points). Overall, fuel-specific NO_x emissions from an average taxi measured in Krakow was 50% higher than other passenger cars.

Buses

Buses were also examined during this campaign. Their fleet composition indicated that the majority of measurements originated from private-sector service operators who are classified as "unknown" are not formally registered with the Krakow transport authority. These were predominantly van-based minibuses with more than half of measurements attributable to pre-Euro 4/IV vehicles and which actually exhibited the study's highest NO_x and PM emissions per amount of fuel burnt. By contrast, the city-run municipal buses had the lowest NO_x and PM g/kg emission levels, with a majority of vehicles being type-approved to Euro VI standard.

Finally, the report studies individual PM measurements of diesel passenger cars and focuses on the highest emitting fraction. The results indicated that vehicles typically equipped with a DPF (i.e. post Euro 4) clearly outperform their predecessors. Only a small minority of the vehicles measured presented PM levels comparable to the median emissions of vehicles typically not equipped with a DPF.

In summary, the Krakow remote sensing campaign has confirmed some lessons learned from previous testing campaign in other European cities, as well as revealing some new insights. The first key point is that urban NO_x emissions from diesel engines generally exceed petrol levels by several times, or at best by 50% for the newest vehicles. The second is that the oldest vehicles contribute disproportionately to air pollution levels due to more lenient baseline emission standards. This is further compounded by the general deterioration of emissions reduction strategies through vehicle ageing and other factors. The issue of vehicle age is particularly visible in this study and therefore we anticipate the problem to be even more pronounced in the national fleet, which is an average of four years older than that of the Krakow metropolitan area.

At the time of the writing, the Krakow clean transport zone had been revoked, however, the city has commissioned this report to better 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 4 petrol and pre-Euro 6 diesel models), could significantly reduce NO_x emissions deliver tangible benefits to air quality.