A comparison of light-duty vehicle NO_x emissions measured by remote sensing in Zurich and Europe

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1. INTRODUCTION

Diesel-fueled passenger cars on the road in real-world operation routinely exceed the laboratory certification limits on nitrogen oxides (NO_x) emissions. The negative impact of these excess NO_x emissions is particularly pronounced in Europe due to ineffective enforcement of Euro emission standards and the high dieselization rate of the European light-duty vehicle fleet. NO_x emissions contribute to persistent air-quality problems in many European cities and adversely affect public health. Real-world measurements of vehicle emissions are needed to understand the actual impact of motor vehicle emissions on air quality, and to inform related policies.

Remote sensing is one technique used to measure real-world NO_x emissions in Europe. Remote sensing equipment can be thought of as a speed camera for vehicle emissions. Emissions are measured remotely via spectroscopy as a vehicle drives by the equipment, making remote sensing a nonintrusive method for measuring real-world emissions. Remote sensing makes it possible to measure emissions from thousands of vehicles in a single day. The snapshot of the exhaust plume content collected from a passing vehicle is equivalent to about one second's worth of emissions data for a single operating condition. Over time, many hundreds or thousands of such snapshots for a given vehicle group can be collated at multiple locations. The result is a realistic picture of the exhaust emissions of that vehicle model over time and over a range of operating conditions (e.g., at different ambient temperatures and vehicle speeds).[1]

In 2016, the Bundesamt für Umwelt (Switzerland's Federal Office for the Environment) funded a 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. Data from the various measurement campaigns has been compiled and supplied by The Swedish Environmental Research Institute (IVL). The so-called CONOX database was accompanied by a series of studies that analyze this unique dataset and compare remote sensing with other measurement techniques.[2] The CONOX data have further been used to quantify real-world NO_x emissions of passenger cars in Europe, with results confirming significant emission exceedances for the vast majority of diesel passenger cars on the road.[3]

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[1] Further information on remote sensing technology and its different applications can be found here: Jens Borken-Kleefeld and Tim Dallmann, *Remote sensing of motor vehicle exhaust emissions* (ICCT: Washington, DC,2018), https://www.theicct.org/publications/vehicle-emission-remote-sensing

[2] 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), 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.

[3] Yoann Bernard et al., *Determination of Real-World Emissions from Passenger Vehicles Using Remote Sensing Data* (ICCT: Washington DC, 2018), https://www.theicct.org/publications/real-world-emissions-using-remote-sensing-data; Yoann Bernard et al., *Explanation of the TRUE Real-World Passenger Vehicle Emissions Rating System* (ICCT: Washington, DC, 2018), https://www.theicct.org/publications/true-real-world-pv-emissions-rating-system.

Remote sensing measurements conducted by the Canton of Zurich are a pillar of the CONOX dataset.[4] Zurich data accounted for more than one-third of light-duty vehicle measurements in the CONOX dataset. Moreover, the Zurich remote sensing data are unique in a number of ways. First, remote sensing campaigns have been conducted in Zurich at the same sites and during the same season every year since 2000. Because the Zurich campaigns are conducted at regular intervals and at fairly consistent ambient and driving conditions, the time series presents an ideal opportunity to monitor vehicle emissions over time.[5] Second, the road at the main measurement site in the Canton of Zurich is considerably steeper than at all other measurement sites in the CONOX data. The steeper road grade results in a higher average estimated engine load in the Zurich data than in data gathered elsewhere.

This paper compares the remote sensing measurements and emissions in Zurich to the rest of the CONOX database, focusing on the effect of estimated engine load on NO_x emissions. Section 2 documents the data sources, describes how data was prepared for analysis, compares measurement conditions in the Zurich and CONOX data, and investigates the relationship between estimated engine load and NO_x emissions. Section 3 presents results for passenger cars and light commercial vehicles by Euro standard and vehicle manufacturer, and estimates annual NO_x emissions of individual vehicle families in Zurich. Section 4 discusses the findings and draws conclusions from the results. Note that, throughout the report, blue graph elements are used for Zurich and brown for CONOX remote sensing data. All whiskers and shaded areas in graphs refer to 95% confidence intervals of the mean.

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[4] J. Sintermann et al., “Langjährige Abgasmessungen Im Realen Fahrbetrieb Mittels Remote Sensing” (Zurich, Switzerland: Kanton Zurich, Amt für Abfall, Wasser, Energie und Luft, April 23, 2018), https://awel.zh.ch/content/dam/baudirektion/awel/luft_asbest_elektrosmog/verkehr/rsd/dokumente/RSD_Bericht_2017.pdf.

[5] Yuche Chen and Jens Borken-Kleefeld, “Real-Driving Emissions from Cars and Light Commercial Vehicles – Results from 13 Years Remote Sensing at Zurich/CH,” Atmospheric Environment 88 (May 2014): 157–64, https://doi.org/10.1016/j.atmosenv.2014.01.040;
Yuche Chen and Jens Borken-Kleefeld, “NOx Emissions from Diesel Passenger Cars Worsen with Age,” Environmental Science & Technology 50, no. 7 (April 5, 2016): 3327–32, https://doi.org/10.1021/acs.est.5b04704;
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.

2. METHODOLOGY

2.1. DATA SOURCES

Remote sensing measurements are used to estimate average real-world emissions. The methodology for analyzing and aggregating remote sensing measurements was described in detail in a previous study.[6] In summary, snapshots of the exhaust plume content and vehicle speed and acceleration are collected from passing vehicles at remote sensing monitoring locations. Road grade and ambient temperature and humidity are also recorded, and pictures of the license plate are taken to identify the vehicle model and engine (personal information is not collected). The emissions data are reported as molar ratios of pollutants to CO_2.

The Zurich remote sensing data were included in the overall CONOX database in previous studies. For this paper, the Zurich data have been separated to compare Zurich with the rest of the CONOX data. This means that the CONOX data presented in this paper are somewhat different from the data reported in previous papers. The CONOX dataset here includes more than 100,000 records measured in London from November 2017 through February 2018.[7] In addition, one of the instruments used across the dataset successively received software improvements between 2016 and 2018, affecting its NO and NO_2 measurements. To ensure comparability across results, each of the concerned CONOX subsets has been reprocessed with the equipment provider's state-of-the art algorithm. Unless otherwise noted, the dataset labeled as "CONOX" in this paper includes data from almost 700,000 measurements, collected in various cities in France, Spain, Sweden, and the United Kingdom. More than 250,000 measurements collected in Switzerland between 2011 and 2017 are benchmarked against this dataset.

2.2. DATA PREPARATION

Distance-specific emission values—pollutant mass in gram per kilometer (g/km)—can be estimated from remote sensing measurements in a two-step process. The first step is to use a carbon balance method to convert to pollutant mass per mass of fuel burned. This is done utilizing the measured amount of carbon monoxide (CO) and hydrocarbons (HCs) relative to tailpipe CO_2, in addition to the approximate carbon weight fraction of a given fuel. The second step is to convert to a unit of pollutant mass per distance traveled, in gram per kilometer (g/km). This can be done by utilizing the average real-world fuel consumption of a given vehicle model (or group of models).[8] Because a single measurement from remote sensing only provides a snapshot of the emissions levels of a vehicle at a given driving condition, a sufficiently large and diverse sample of measurements is needed to calculate average emissions.

The load on the engine can have a significant impact on emissions. Thus, it is important to record and evaluate the effect of vehicle speed, vehicle acceleration, and road grade on the engine load. In this study, and in much of the literature on vehicle emissions remote sensing, the engine load is estimated using calculations of the vehicle-specific

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[6] Bernard et al., *Determination of Real-World Emissions from Passenger Vehicles Using Remote Sensing Data*.

[7] Tim Dallmann et al., *Remote Sensing of motor vehicle emissions in London* (ICCT, December 18, 2018), https://www.theicct.org/publications/true-london-dec2018.

[8] Bernard et al.; David C. Carslaw Recent evidence concerning higher NOx emissions from passenger cars and light duty vehicles. *Atmospheric Environment*, 45, no. 39, 7053–63 https://doi.org/10.1016/j.atmosenv.2011.09.063

power (VSP) at the wheel. VSP is calculated from vehicle speed, acceleration, the grade of the road, and estimates of aerodynamic drag and tire rolling resistance. Numerous formulas have been developed to calculate VSP. Zurich used the formula developed by Jiménez-Palacios.[9] To ensure comparable estimates across the different data sources in this study, VSP was recalculated for all data using the following formula:[10]

$$VSP = v \times (9.81 \text{ x } sine(slope) + 1.1 \times a + 0.213 + 3.04 \times 10^{-4} \times v^2),$$

where *VSP* refers to vehicle-specific power in kilowatt per ton (kW/t), *v* refers to vehicle speed in meters per second (m/s), *slope* refers to road grade in degrees, and *a* refers to vehicle acceleration in m/s^2.

Emissions comparisons in this paper include comparisons across manufacturer groups and vehicle families. The Appendix lists the manufacturer groups (and their respective brands) used in this paper. Individual vehicles were also grouped into vehicle families, which are vehicles of the same fuel type, Euro standard, manufacturer group, and engine displacement. Development of the vehicle family grouping and the rationale for the grouping were described in detail in an earlier study.[11]

2.3. COMPARISON OF ZURICH AND CONOX TESTING CONDITIONS

Table 1 compares the measured vehicles and the testing conditions between Zurich and the rest of the remote sensing data collected as part of the CONOX project. Most combinations of emission standards and fuel types contain several thousand valid measurements in both Zurich and the rest of the CONOX data. Consistent with the fleet composition in European countries, relatively old (Euro 2) and new (Euro 6) vehicles tend to be less common in the sample than vehicles that were three to twelve years old at the time of measurement (Euro 3 through Euro 5). Median certified CO_2 values have declined over time, particularly after EU-wide CO_2 standards for new cars were introduced in 2009. Median certified CO_2 values in Zurich were consistently higher than for the rest of the CONOX vehicles, indicating that these vehicles were larger and heavier than the samples from other countries.

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[9] José Luis Jiménez-Palacios, *Understanding and quantifying motor vehicle emissions with vehicle specific power and TILDAS remote sensing* (Doctoral thesis, Massachusetts Institute of Technology, 1999). Retrieved from https://dspace.mit.edu/handle/1721.1/44505

[10] Formula from the EPA guidance document (U.S. EPA, 2004) converted to the International System of Units (SI). U.S. Environmental Protection Agency. (2004, July). "Guidance on use of remote sensing for evaluation of I/M program performance, EPA420-B-04-010," Retrieved from https://nepis.epa.gov/Exe/ZyPdf.cgi?Dockey=P1002J6C.pdf

[11] Bernard et al., *Determination of Real-World Emissions from Passenger Vehicles Using Remote Sensing Data*.

Table 1. Comparison of Zurich (blue) and CONOX (brown) remote sensing test conditions for passenger cars.

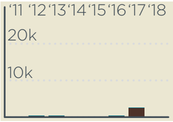
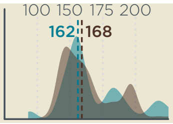
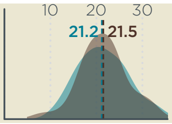
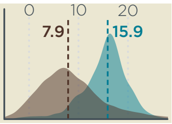
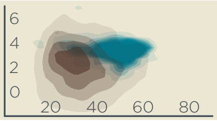
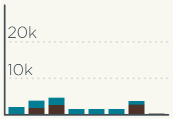
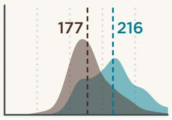
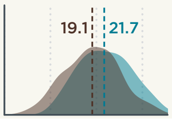
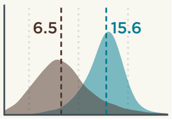
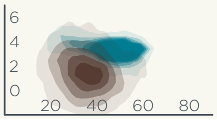
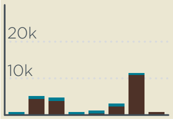
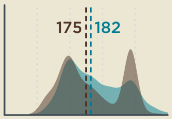
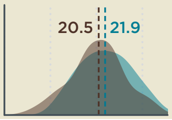
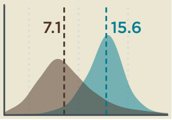
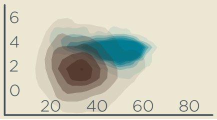
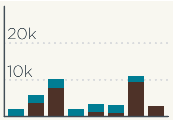
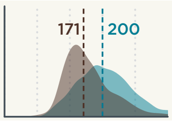
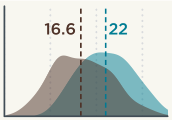
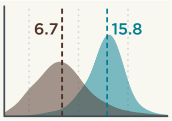
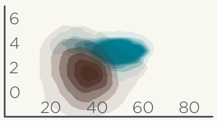
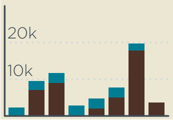
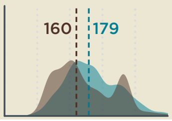
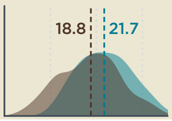
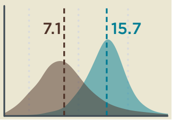
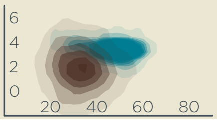
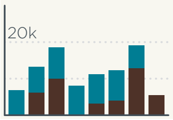
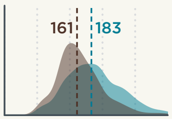
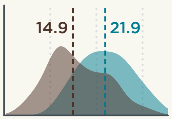
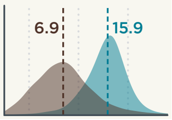
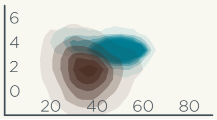
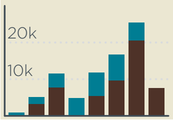
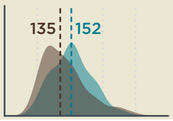
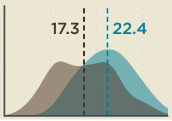
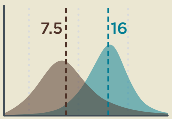
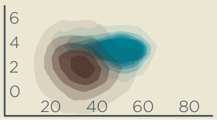
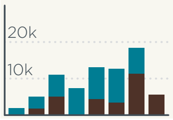
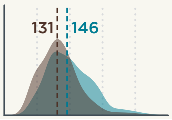
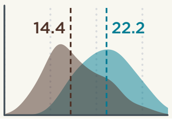
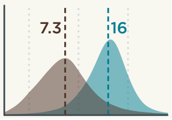
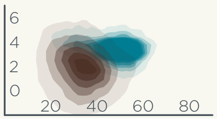
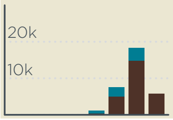
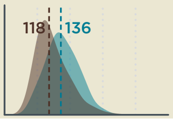
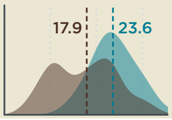
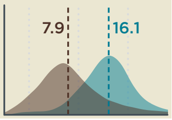
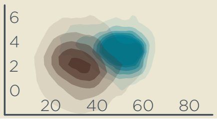
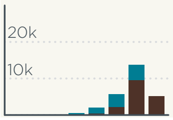
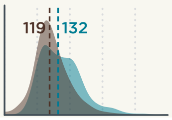
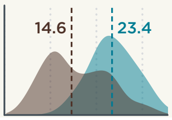
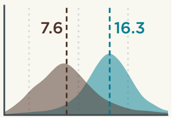
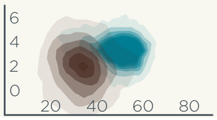
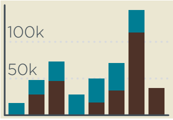
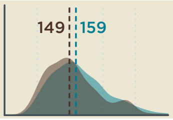
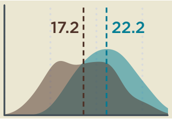
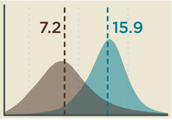
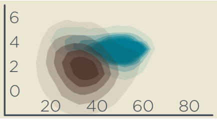
	Measurements	Avg. vehicle age (years)	Avg. road grade	Measurements per year	Certified CO$_2$ emissions (g/km, NEDC)	Ambient temperature (°C)	Vehicle-specific power (kW/ton)	Acceleration (km/h/s) over speed (km/h)
Euro 2 Diesel	666 3,620	16 17	9.0% 2.9%					
Euro 2 Gasoline	11,043 8,198	16 16	9.1% 2.5%					
Euro 3 Diesel	5,073 22,831	12 12	9.1% 2.5%					
Euro 3 Gasoline	14,251 26,316	13 12	9.1% 2.3%					
Euro 4 Diesel	17,194 44,900	8 7	9.1% 2.4%					
Euro 4 Gasoline	52,744 41,841	9 8	9.1% 2.3%					
Euro 5 Diesel	29,679 54,186	4 4	9.0% 2.6%					
Euro 5 Gasoline	43,205 31,749	4 4	9.0% 2.5%					
Euro 6 Diesel	7,067 26,231	2 1	8.7% 2.6%					
Euro 6 Gasoline	9,868 17,341	2 1	8.7% 2.4%					
Total	191k 277k	7 7	9.1% 2.5%					

Figure 1 provides additional insights into differences in Euro 6 diesel vehicles sampled in Zurich and the other remote sensing sites. It plots average type-approval CO_2 emissions and the fleet composition for the 10 most commonly measured manufacturer groups of Euro 6 diesel passenger cars in Zurich. Zurich has considerably more Daimler, BMW, and Volkswagen Group measurements than other sites; and fewer from PSA Group, Ford, and other manufacturer groups. This skews the average toward (German) premium manufacturers and higher certified CO_2 values. In addition, the CO_2 values are higher in the Zurich data for all manufacturer groups, with the most notable differences recorded for Hyundai Motor Company, Daimler, BMW, and Mazda. This discrepancy between Zurich and CONOX data is in line with documented differences between the Swiss and EU car markets, with vehicles sold in Switzerland, on average, having higher certified CO_2 emissions and being larger, heavier, and more powerful.[12]

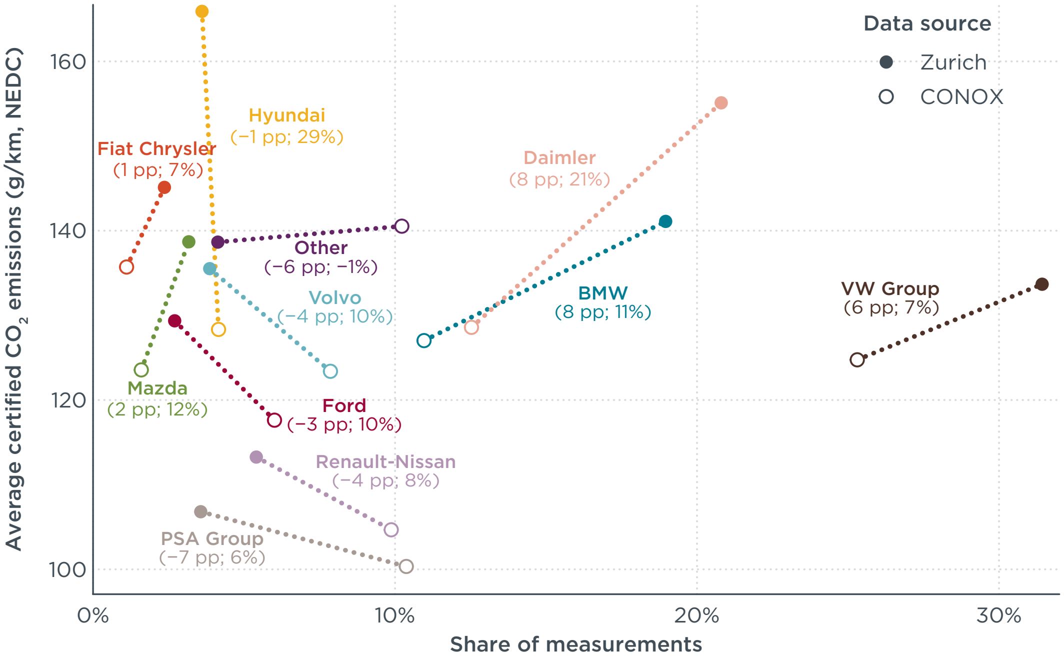


Figure 1. Manufacturer group shares of measurements and mean certified CO_2 emissions for Euro 6 diesel passenger cars in Zurich and CONOX remote sensing data. The first value in brackets represents the difference, in percentage points (pp), between each manufacturer group's share of Zurich and CONOX measurements. The second value is the percentage difference between mean certified CO_2 emissions.

The measurements per year column in Table 1 shows that the year of data collection varies significantly between Zurich and the rest of the data over the different emission standards and fuel types. For example, the Zurich data for Euro 4 gasoline vehicles is reasonably uniformly distributed between 2011 and 2017, while the rest of the CONOX data is concentrated in 2012, 2013, and 2017. This non-uniformity results from the unique fleet characteristics in each country as well as the relatively limited number of measurement campaigns spread across eight years. Additional remote sensing campaigns will further diversify the data.

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[12] Peter Mock (Ed.)(2018). *European vehicle market statistics, 2018/2019*, (ICCT, Washington, DC, 2018) https://www.theicct.org/publications/european-vehicle-market-statistics-20182019

The ambient temperature column in Table 1 shows a growing difference in the median ambient temperature at which data was collected in Zurich and the rest of the remote sensing sites. For Zurich, the median temperature rose slightly from approximately 21°C for Euro 2 to 23°C for Euro 6. For the rest of the CONOX data, the median temperature dropped from 21°C for Euro 2 diesels to as low as 14.6°C for Euro 6 gasoline vehicles due to some recent remote sensing samples being collected during the winter 2017–2018, leading to lower average ambient temperature for more modern vehicles.

The influence of the steep road grade at the Zurich sites is clearly reflected in the VSP distribution, with the median VSP from Zurich typically at least twice as high as the median VSP in the rest of the CONOX data. The contour maps in the rightmost column plot vehicle acceleration on the y-axis over speed on the x-axis. The acceleration values consider both the vehicle's longitudinal acceleration and the gravitational component due to uphill driving to make acceleration values more comparable. The higher acceleration values in Zurich are thus partly due to the 9% average road grade at the Zurich sites. The contour maps also show that average vehicle speeds typically were higher at the Zurich site than for the rest of the CONOX data. Vehicle speed and acceleration both affect VSP, which is why the VSP differences between Zurich and the rest of the data are higher than the individual acceleration and speed differences. In the Zurich data, the VSP distributions and the contour maps are extremely consistent across all emission standards and fuel types, with average VSP of about 16 kW/ton, average speed between 40 and 60 km/h, and average acceleration (including road grade effects) of 3 to 4 km/h/s. This suggests that driving patterns at Zurich remote sensing sites were fairly consistent over time. In the rest of the CONOX data, speed and acceleration were much more widely distributed.

Despite the high road grade in Zurich, acceleration rates of 3 to 4 km/h/s at speeds between 40 and 60 km/h are fairly moderate. Figure 2 shows the distribution of power demand relative to the declared maximum power output of the vehicles in Zurich and in CONOX data. More specifically, the figure plots the ratio of calculated VSP of each vehicle over its respective maximum power-to-mass ratio. The distribution confirms that vehicles tend to be measured at higher power demand in Zurich than at other CONOX sites. Median relative power demand in Zurich was 24%,13 percentage points higher than in other CONOX data, but virtually all vehicles were measured at less than 50% of their maximum power output. These results suggest that engine loads in the Zurich data are not excessive.

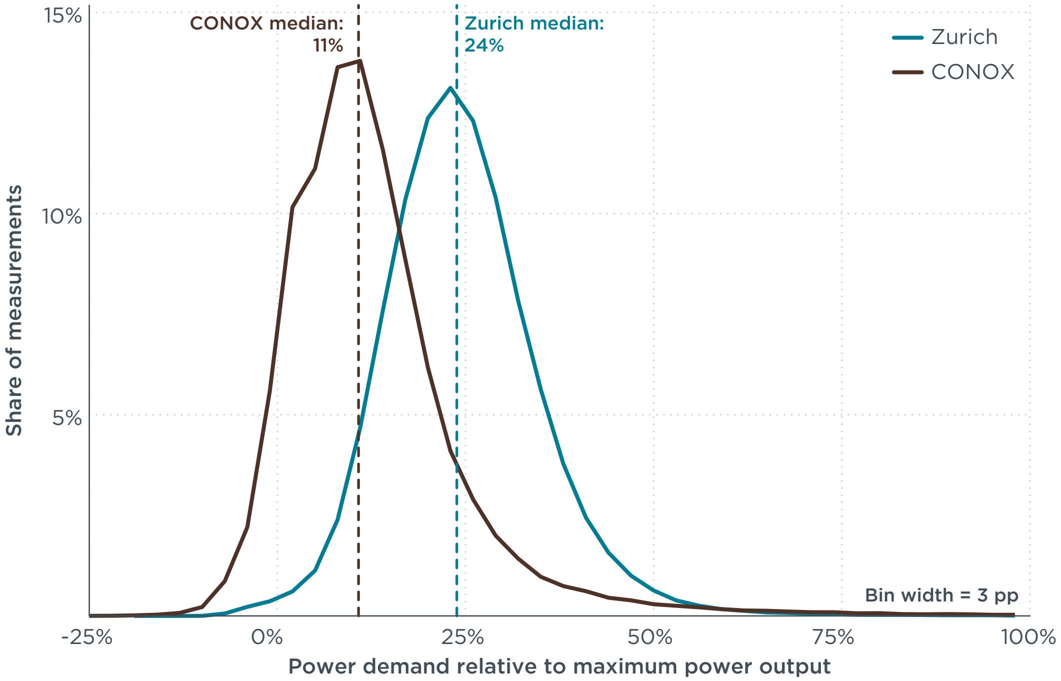

Figure 2: Distribution of Zurich and CONOX measurements in terms of power demand (VSP) relative to the maximum power output. The maximum power-to-mass ratio of each vehicle was calculated using the rated engine power and curb weight, with an additional 100 kg for the average mass of the driver plus potential occupants.

In summary, the comparison of vehicle characteristics and driving conditions highlights several important differences between Zurich and CONOX data. For one, Zurich's vehicle fleet tends to skew toward heavier, larger, and more premium vehicles with higher certified CO_2 emission values. Moreover, driving conditions were more demanding in Zurich, particularly due to the comparatively high road grade. These differences inform the analysis of NO_x emissions because VSP has been shown to influence emissions, and emission levels can vary significantly across manufacturer groups. Lastly, the Zurich data is unique due to the sampling design, with measurements being conducted on an annual basis, at the same sites, and under comparable ambient conditions. The rest of the CONOX data are more susceptible to variations in fleet and testing conditions, as samples were collected in various countries and during different seasons.

2.4. COMPARISON WITH REAL DRIVING EMISSIONS DYNAMIC BOUNDARY CONDITIONS

Metrics other than VSP can be used to characterize driving conditions. The Real Driving Emissions (RDE) regulation defines limits based on the product of vehicle speed and longitudinal acceleration (V×A). The 95th percentile of V×A relative to vehicle speed is used to evaluate whether a trip is valid or too dynamic.[13] Figure 3 plots V×A over speed from all remote sensing measurements. The heat map represents the density of measurements. Brown markers represent the 95th percentile of V×A per speed bin,

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[13] Peter Mock and Gabriella Perotti, "Real-Driving Emissions test procedure for exhaust gas pollutant emissions of cars and light commercial vehicles in Europe (ICCT, January 2017), https://www.theicct.org/publications/real-driving-emissions-test-procedure-exhaust-gas-pollutant-emissions-cars-and-light.

which is compared with RDE limits. The acceleration component takes into account gravitational forces from uphill driving.[14]

Figure 3 shows that the vast majority of remote sensing measurements in the full CONOX dataset comply with the RDE limit. The RDE limit on V×A is only exceeded at higher vehicle speeds, for which comparatively few remote sensing measurements are available.

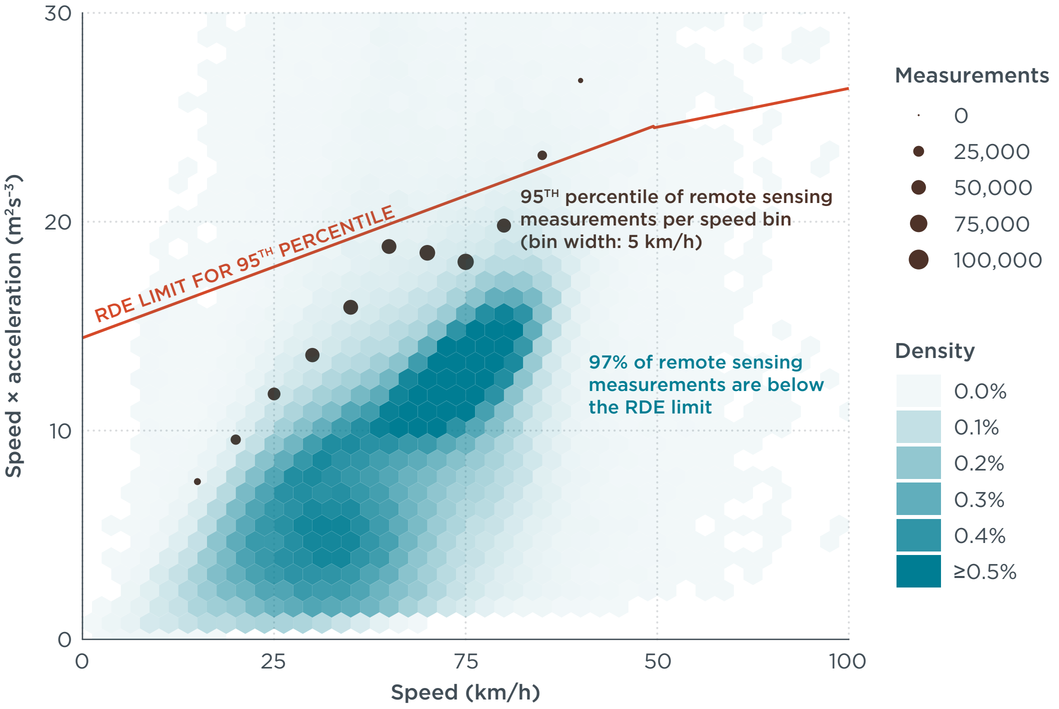

Figure 3: Vehicle speed times acceleration in CONOX remote sensing dataset compared with the RDE 95th percentile limits. Brown markers represent the 95th percentile and the number of measurements per speed bin.

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[14] RDE-compliant trips must start and end at similar altitudes. Therefore, gravitational forces during RDE trips are neglected for the comparison with remote-sensing of VxA.

3. ANALYSIS AND RESULTS

3.1. NO_x EMISSIONS BY EURO STANDARD

Figure 4 summarizes average remote sensing fuel-specific NO_x emissions, in grams NO_x per kilogram fuel (g/kg), for diesel and gasoline passenger cars from Euro 2 to Euro 6. Figure 5 converts the fuel-specific emissions to distance-specific NO_x emissions, using the method described in Section 2.2. The trends are the same in both figures, and differences between Zurich and the rest of the CONOX data are similar.

What is immediately apparent in Figure 4 and Figure 5 is that NO_x emissions from gasoline vehicles decreased proportionally to reductions in the type-approval limit, while real-world diesel NO_x emissions leveled off from Euro 4 through Euro 5 before significantly declining with the introduction of the Euro 6 standard. The trends and emissions levels in Zurich data are consistent with previous studies of Zurich remote sensing data.[15] Diesel NO_x emissions measured in Zurich were similar to the rest of the CONOX data, despite the more demanding driving conditions in Zurich. Gasoline NO_x emissions were consistently lower in Zurich, by about 29%–78% per Euro standard on a fuel-specific basis and 21%–57% on a distance-specific basis.

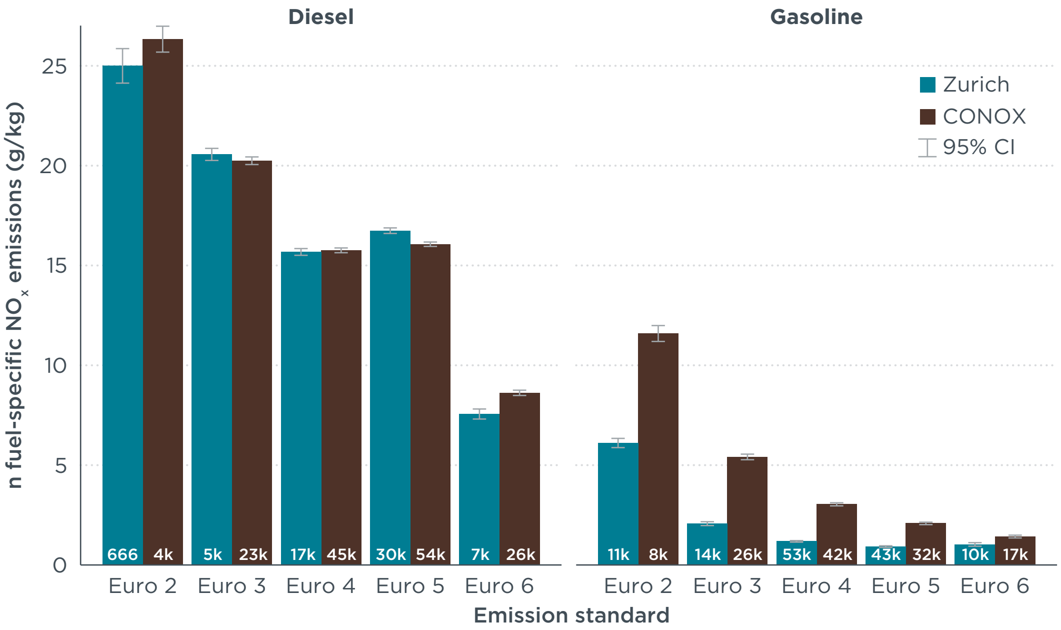

Figure 4. Mean fuel-specific NO_x emissions for diesel and gasoline passenger cars, grouped by Euro standard, for Zurich and CONOX remote sensing data. The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean.

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[15] J. Sintermann et al. (2018)., "Langjährige Abgasmessungen im realen Fahrbetrieb mittels Remote Sensing" (Zurich, Switzerland: Kanton Zurich, Amt für Abfall, Wasser, Energie und Luft, April 23, 2018), https://awel.zh.ch/content/dam/baudirektion/awel/luft_asbest_elektrosmog/verkehr/rsd/dokumente/RSD_Bericht_2017.pdf.

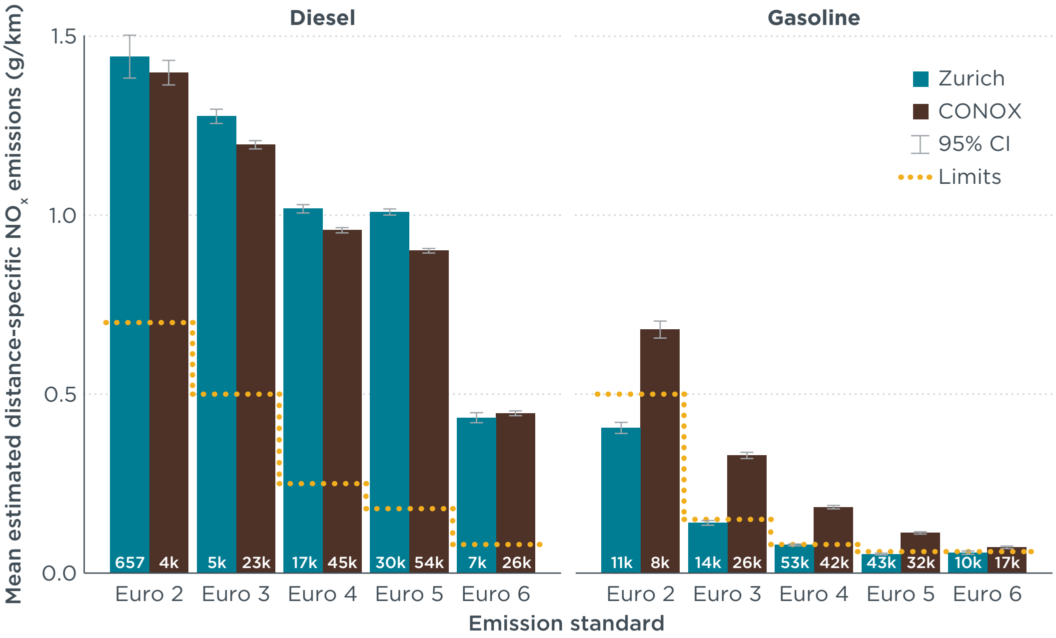

Figure 5. Mean distance-specific NO_x emissions for diesel and gasoline passenger cars, grouped by Euro standard, for Zurich and CONOX remote sensing data. The number of measurements is presented at the bottom of each bar. Whiskers represent the 95% confidence interval of the mean.

VSP is known to be an important determinant of NO_x emissions, especially for diesel vehicles.[16] Figure 6 compares the average fuel-specific diesel passenger car NO_x emissions with VSP observed in the Zurich and CONOX data for Euro 3 through Euro 6 emission standards. Generalized additive models, as implemented in the *mgcv*[17] and *ggplot2*[18] packages for the R software environment[19], were used to plot the relationship between NO_x and VSP. The VSP range is truncated, from 5th to 95th percentile per group, to avoid plotting relationship for ranges with scarce data.[20]

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[16] 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; Bernard et al., *Determination of Real-World Emissions from Passenger Vehicles Using Remote Sensing Data*.

[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, Use R!” (New York: Springer, 2009).

[19] R Core Team, “R: A language and environment for statistical computing” (Vienna, Austria: R Foundation for Statistical Computing, 2018), http://www.R-project.org/.

[20] Chen and Borken-Kleefeld, *Real-Driving Emissions from Cars and Light Commercial Vehicles – Results from 13 Years Remote Sensing at Zurich/CH*.

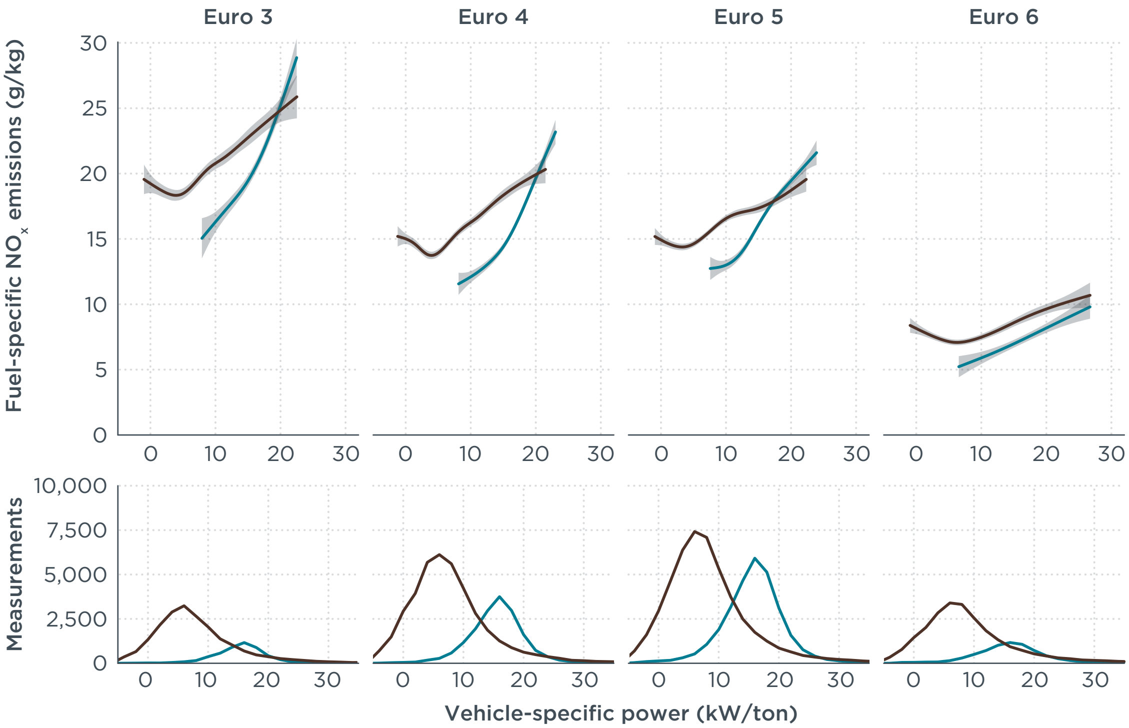

Figure 6. Top graph: Comparison of fuel-specific NO_x emissions of Euro 3 through Euro 6 diesel passenger cars as a function of VSP in Zurich (blue) and CONOX (brown) remote sensing data. Relationship between NO_x emissions and VSP represented using generalized additive models with 95% confidence intervals. Bottom graph: Number of measurements in each data source per VSP bin (bin width: 2 kW/ton).

The brown lines in the upper graph (for the rest of the CONOX data) show that the fuel-specific NO_x emissions are lowest at a VSP around 5 kW/t, but increase below and above. Zurich (blue lines) measurements are scarce below 6 kW/t and show increasing emissions with increasing VSP. In the range where both Zurich and CONOX data overlap (see bottom graph), the two datasets agree reasonably well and confirm that VSP has significant impacts on diesel NO_x emissions. At low VSP, Zurich measurements furnish lower estimates of NO_x emissions. The increase in fuel-specific NO_x emissions below 3 kW/t is probably caused by a reduction in CO_2 concentrations with lower engine load. The absolute mass of NO_x emitted at these low VSP values is in fact small.

Despite the more demanding driving conditions at Zurich remote sensing sites compared with the rest of the CONOX measurements, diesel passenger cars emitted similar levels of NO_x (see Figure 5). Figure 7 plots the relationship between NO_x emissions and VSP for diesel passenger cars for different Euro standards and ambient temperature bins. The VSP range is truncated, from 5th to 95th percentile per group, to avoid plotting relationships for ranges with scarce data. While NO_x emissions increase with VSP for all Euro standards and ambient temperature ranges, NO_x emissions levels are elevated below 10°C. A similar impact of ambient temperature on NO_x emissions from diesel passenger cars was observed in a 2016 measurement campaign performed in Gothenburg, Sweden.[21] Zurich measurements were consistently conducted during summer months, but other CONOX measurements were conducted during different seasons, skewing the other CONOX measurements toward lower temperatures, albeit at lower VSP levels (see Table 1). Figure 7 thus suggests that wintertime remote sensing campaigns in the CONOX data elevated average NO_x emission levels compared with the mild temperature ranges during Zurich campaigns, producing similar estimates of average NO_x emissions from diesel passenger cars despite the higher VSP levels in Zurich. Further study is needed to disentangle VSP, ambient temperature, and other effects inherent in the diverse CONOX dataset.

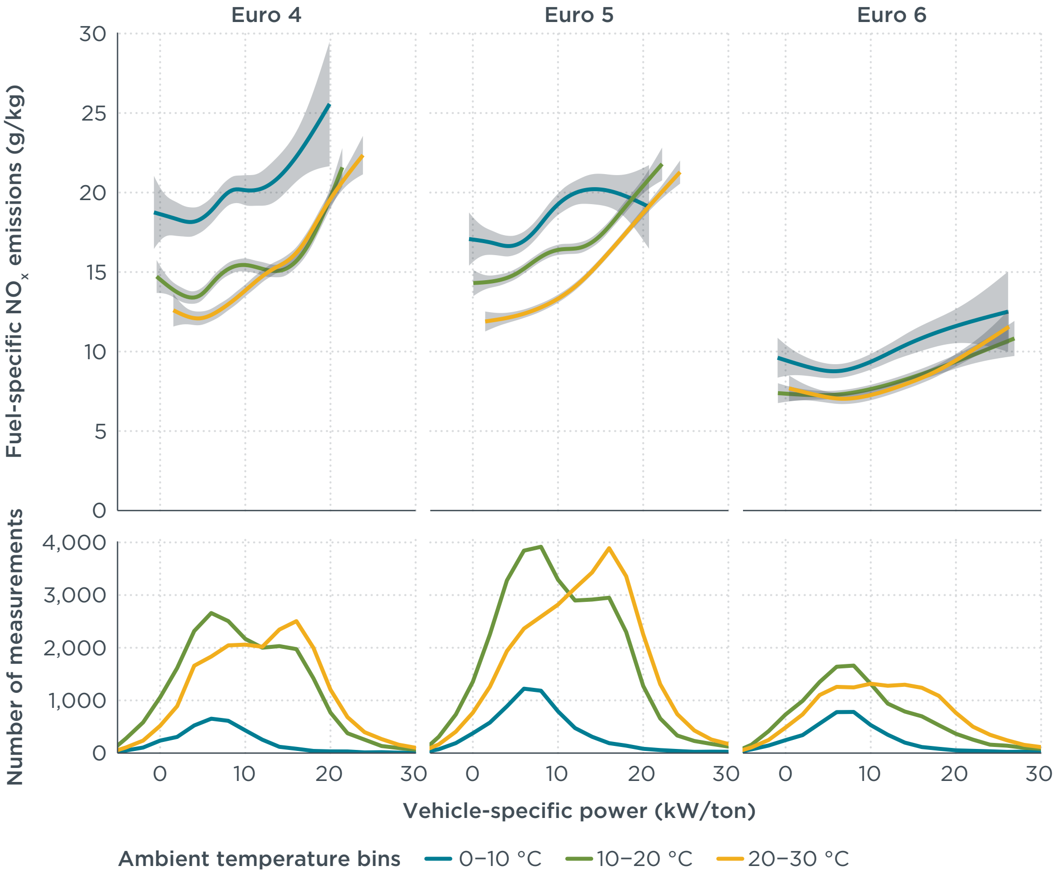

Figure 7. Top graph: Fuel-specific NO_x emissions of diesel passenger cars as a function of VSP per Euro standard and ambient temperature bin. Relationship between NO_x emissions and VSP represented using generalized additive models with 95% confidence intervals based on the full dataset (CONOX and Zurich remote sensing data). Bottom graph: Number of measurements in each ambient temperature bin (bin width: 10°C) and VSP bin (bin width: 2 kW/ton).

Whereas Figure 6 and Figure 7 focus on diesel passenger cars, Figure 8 graphs fuel-specific NO_x emissions of gasoline passenger cars as a function of VSP for Euro 3 through Euro 6 vehicles. The lines in Figure 8 were generated using generalized additive

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[21] Åke Sjödin et al., "On-road emission performance of late model diesel and gasoline vehicles as measured by remote sensing" (IVL Swedish Environmental Research Institute, June 2017), https://www.ivl.se/download/18.449b1e1115c7dca013adad3/1498742160291/B2281.pdf.

models for NO_x on VSP, by Euro standard, using the full dataset (CONOX + Zurich).[22] The markers represent average measured NO_x (filled markers) as well as average predicted NO_x (unfilled markers) for the average VSP in Zurich and the rest of the CONOX data. The figure indicates that NO_x emission levels of gasoline passenger cars tend to decline with VSP increases at approximately 7–15 kW/ton, an effect that is particularly pronounced in older emission standards. The round markers representing averages in CONOX and Zurich data indicate that VSP explains a sizeable portion of the observed differences between Zurich and CONOX average NO_x emission values in Figure 4 and Figure 5, but that other effects should be studied as well.

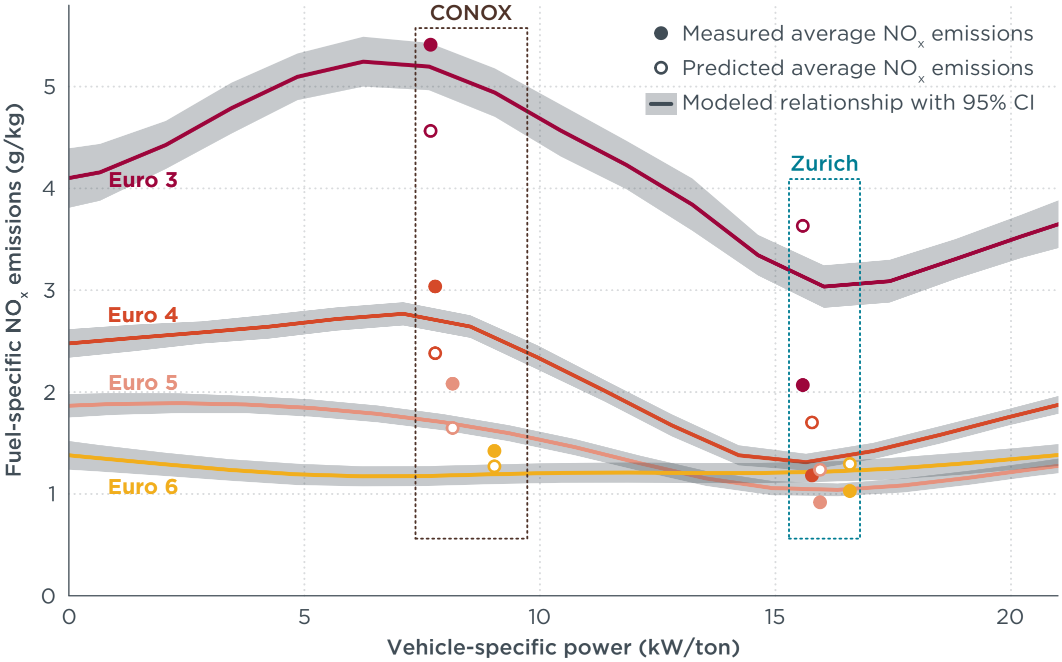

Figure 8. Fuel-specific NO_x emissions of gasoline passenger cars as a function of VSP. Relationship between NO_x emissions and VSP represented using generalized additive models based on the full dataset (CONOX and Zurich remote sensing data). Markers denote average VSP as well as average measured NO_x emissions (filled markers) and average model predictions (unfilled markers) for CONOX and Zurich data.

Figure 9 presents average fuel-specific NO_x emissions from diesel and gasoline light commercial vehicles (LCVs) from Euro 2 to Euro 6.[23] Approximately 96% of new LCVs are diesel-fueled, so data for gasoline LCVs is scarce.[24] As a result, the confidence intervals are larger and results are not shown for gasoline Euro 6 vehicles for lack of data (fewer than 100 measurements).

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[22] It would be better to use a subset of the dataset (e.g., Zurich data only), but data availability is an issue: As illustrated in Figure 5, VSP coverage of both Zurich and CONOX are limited. Future studies should repeat this exercise using a subsample to train the models and apply the models to external data to validate them.

[23] There is no distance-specific version of the LCV chart because variance in certification CO_2 values for LCVs make determining appropriate values much more difficult than for passenger cars. Relatively small LCVs (low CO_2) and very large LCVs (high CO_2) can be equipped with the same engine. This issue will be further examined in future papers.

[24] Mock, “European Vehicle Market Statistics—Pocketbook 2018/2019.”

LCV emission levels are generally somewhat higher than the passenger car emissions on a fuel-specific basis. For example, Euro 3 through Euro 6 LCV diesel NO_x emissions in Zurich are about 25%–31% higher than the passenger car diesel NO_x emissions in Figure 4. The differences between LCVs and passenger cars are less pronounced in the CONOX data. Otherwise, the emission trends are similar to the passenger car emissions in Figure 4 and are consistent with earlier literature (e.g., diesel LCV NO_x emissions are relatively constant from Euro 1 through Euro 5).[25] Differences between Zurich and CONOX LCV data are also consistent with the differences for passenger cars in Figure 4: Diesel NO_x emission levels are similar in Zurich and CONOX data whereas gasoline NO_x emission levels are higher in the rest of the CONOX data.

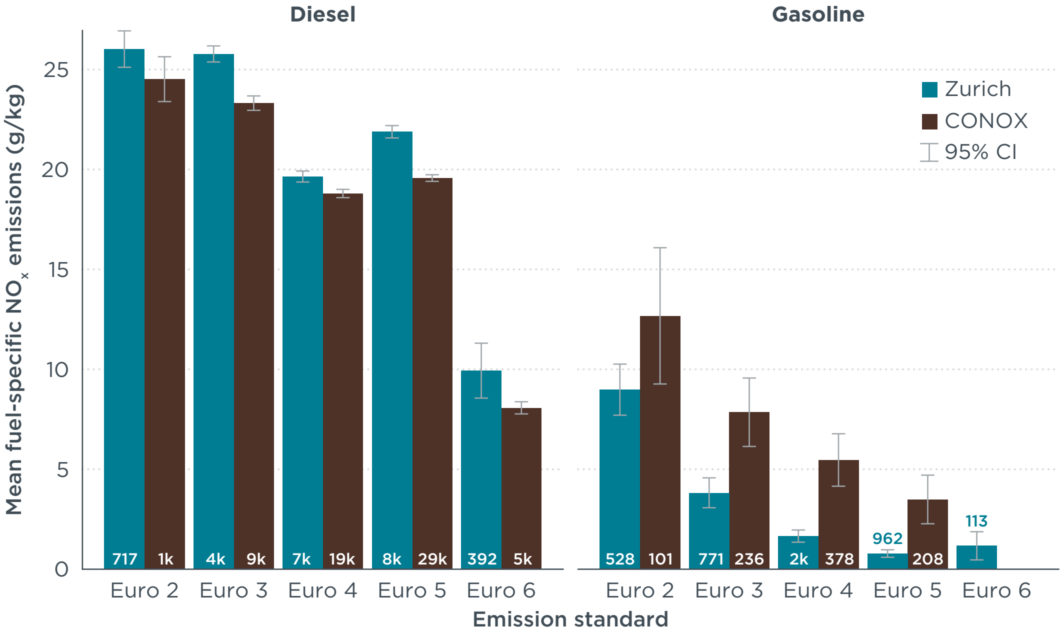

Figure 9. Mean fuel-specific NO_x emissions for diesel and gasoline LCVs, grouped by Euro standard, for Zurich and CONOX remote sensing data. The number of measurements is presented at the bottom of each bar. Data are not shown where fewer than 100 measurements were available per group. Whiskers represent the 95% confidence interval of the mean.

3.2. DIESEL NO_X EMISSIONS BY MANUFACTURER GROUP

Figure 10 plots fuel-specific NO_x emissions for Euro 6 diesel passenger cars of the 10 most commonly measured car manufacturer groups. The figure also includes diesel LCV measurements where possible, although most were removed because there were fewer than 100 measurements for the group.

Diesel NO_x emissions varied considerably by manufacturer. For Zurich passenger cars, the best manufacturers—BMW, Daimler, and VW Group—had average NO_x emissions below 5 g/kg fuel. Renault-Nissan emissions were about 6 times higher and Ford and Fiat-Chrysler 3 or more times higher than the best performers. For the most part, manufacturer group performance was similar in the CONOX data, although the NO_x differences were much more compressed. The three best passenger car groups had

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[25] Chen and Borken-Kleefeld, “Real-Driving Emissions from Cars and Light Commercial Vehicles – Results from 13 Years Remote Sensing at Zurich/CH.”

emissions of 5–7 g/kg fuel, higher than for Zurich, while the other groups generally had lower emissions in CONOX data compared with Zurich. Renault-Nissan had the highest emissions in the CONOX data, but at 20 g/kg compared with 32 g/kg in the Zurich data.

For the six manufacturer groups with at least 100 measurements for LCVs in the rest of the CONOX data, LCV NO_x emissions were the same or lower than for passenger cars for all six groups. This is in line with trends in Figure 4 and Figure 9, where emissions from Euro 6 diesel LCVs in the CONOX data tended to be similar to passenger car levels. For PSA group, the only manufacturer group with at least 100 measurements from Zurich, LCV NO_x emissions were more than twice passenger car NO_x emissions.

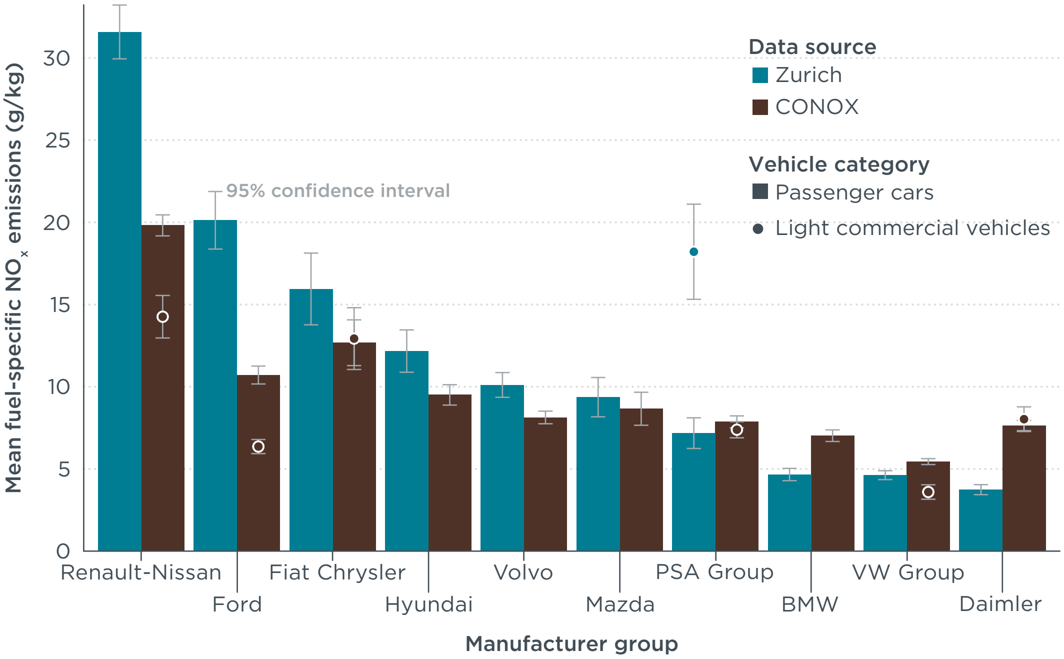

Figure 10. Mean fuel-specific NO_x emissions of diesel Euro 6 passenger cars (bars) and LCVs (round markers). Data presented for the ten most common manufacturer groups in Zurich remote sensing data, ordered by descending mean fuel-specific passenger car NO_x emissions in Zurich. Markers omitted for groups with fewer than 100 measurements. Whiskers represent the 95% confidence interval of the mean.

Some of the differences between Zurich and CONOX manufacturer group results in Figure 10 can be explained by VSP. As shown in Table 1, power demand was considerably higher at Zurich remote sensing sites than in other CONOX measurement campaigns. Figure 11 uses the same generalized additive model discussed for Figure 8 to investigate the relationship between NO_x emissions and VSP. The models were based on all available remote sensing data for Euro 6 diesel passenger cars, including both Zurich and CONOX data. We selected three manufacturer groups from Figure 10 as examples for this analysis: the two manufacturer groups with the highest difference between Zurich and CONOX results, Renault-Nissan and Ford; and the manufacturer group with the lowest difference, VW Group. Figure 11 shows that the relationship between NO_x emissions and VSP varies by manufacturer and is consistent with the differences between the Zurich and CONOX results; the manufacturers with large differences between Zurich and CONOX results, Renault-Nissan and Ford, show a marked increase in NO_x emissions as

VSP increases, while this is not the case for the VW Group. The figure indicates that, for Renault-Nissan and Ford, the difference in average VSP levels accounts for more than half of the measured difference in NO_x emissions between Zurich and CONOX remote sensing data.

Note that the generalized additive model predicts that VSP has relatively little impact on low-NO_x vehicles and has a much larger impact on vehicles with higher NO_x emissions. The most plausible explanation is that most of the higher diesel NO_x emissions at higher VSP are due to changes in emission control calibration at higher engine loads on some vehicles, not due to the higher load itself. Note that this explanation is consistent with the much smaller sensitivity of NO_x emissions to higher load found on gasoline vehicles and with the finding from Figure 10 that the three lowest diesel NO_x groups did not increase NO_x emissions when subjected to Zurich's much higher VSP. Robust emission control calibrations appear to minimize the impact of engine load on NO_x emissions. Best-performing manufacturers tend to perform better in a wide range of VSP, not only at low-load operation.

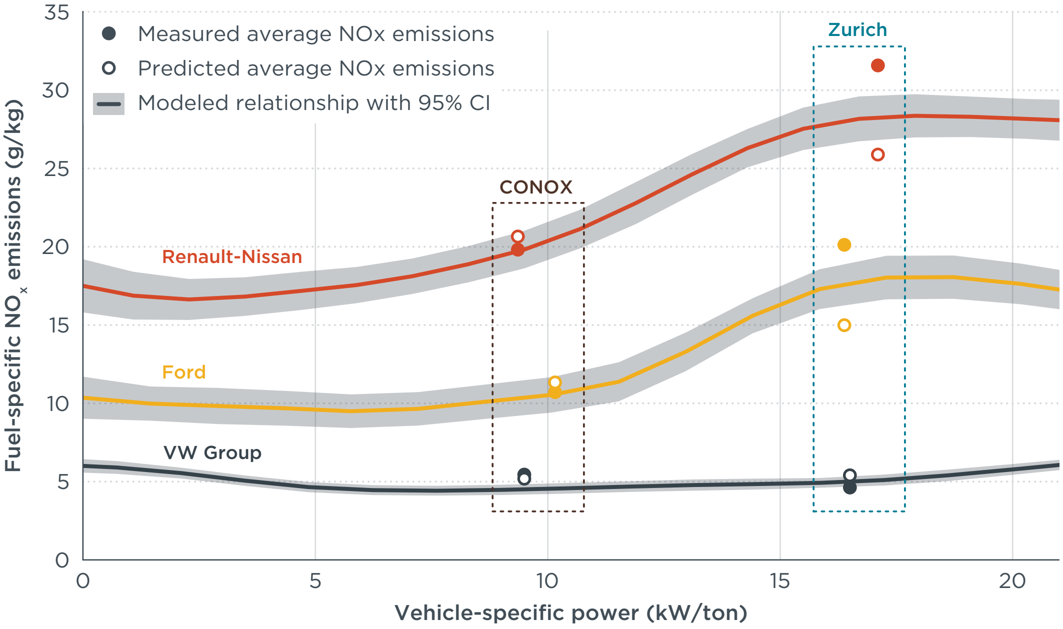

Figure 11. Fuel-specific NO_x emissions as a function of VSP for Euro 6 diesel passenger cars of three select manufacturer groups. The relationship between NO_x emissions and VSP was modeled using generalized additive models. Filled markers denote average VSP and NO_x emissions in Zurich and CONOX remote sensing data for each manufacturer group. Unfilled markers denote corresponding model predictions.

3.3. DIESEL NO_x EMISSIONS BY VEHICLE FAMILY

Analyzing emissions by vehicle family turns remote sensing into a valuable screening tool for regulators and researchers. Figure 12 plots the average estimated distance-specific NO_x emissions of each diesel vehicle family and compares the Zurich results with the rest of the CONOX data results. Only vehicle families with at least 30 measurements in both Zurich and CONOX data were plotted. Euro 3 through Euro 6 vehicles are plotted separately. The laboratory emissions limit for each standard is also included for context.

Average NO_x emissions of all 158 Euro 3 through Euro 6 diesel vehicle families depicted in Figure 12 were higher than their respective laboratory type-approval limits. All Euro 5 families emitted at least twice as much NO_x as the limit and the worst families had emissions over 10 times the limit. The data show almost no improvement in average diesel NO_x emissions as the emission limits were lowered from Euro 3 to Euro 5, even though these standards cover 15 years of technology development. This suggests that deterioration of the emissions control system over time may not be a significant factor for many of the diesel vehicles currently on the road.

The better Euro 6 vehicle families have much lower emissions than the best Euro 5 families, with about half of the families having real world emissions below 0.5 g/km. However, the worst Euro 6 families are not significantly better than the worst Euro 5 families, with on-road emissions estimated at up to 2.0 g/km, or 25 times the Euro 6 standards.

The 1.6- and 1.5-liter Euro 6 diesel engines from the Renault-Nissan group were the two highest emitting Euro 6 families measured in Zurich with sufficient data to evaluate. These results are in line with previous independent testing campaigns performed by EU member states using a portable emissions measurement system (PEMS).[26] In addition, the ICCT previously commissioned PEMS tests on a Nissan Pulsar using the same 1.5-liter Euro 6 diesel engine.[27] The vehicle emitted, on average, 1.3 g/km of NO_x under driving compliant with the RDE regulation and emitted 2.1 g/km under more dynamic driving, 16 and 26 times the Euro 6 laboratory limit, respectively. The Zurich remote sensing results for that vehicle family fall between the RDE-compliant and dynamic on-road tests at an average level of 1.7 g/km, or 21 times the standard.

In general, for Euro 3 through Euro 5 vehicle families, there is a reasonably good match between the data from Zurich and the rest of the CONOX sites, with the linear regression line close to a 1:1 ratio. However, for Euro 6, the linear regression slope is significantly higher than the 1:1 ratio. This regression line is “lifted” by vehicle families of manufacturers shown in Figure 11 to be sensitive to VSP (Renault-Nissan and Ford, among others).

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[26] Bernard et al., *Determination of Real-World Emissions from Passenger Vehicles Using Remote Sensing Data*.

[27] Athanasios Dimaratos et al., *Real-World Emissions Testing on Four Vehicles*, (ICCT: Washington, DC, 2017), https://www.theicct.org/publications/real-world-emissions-testing-four-vehicles.

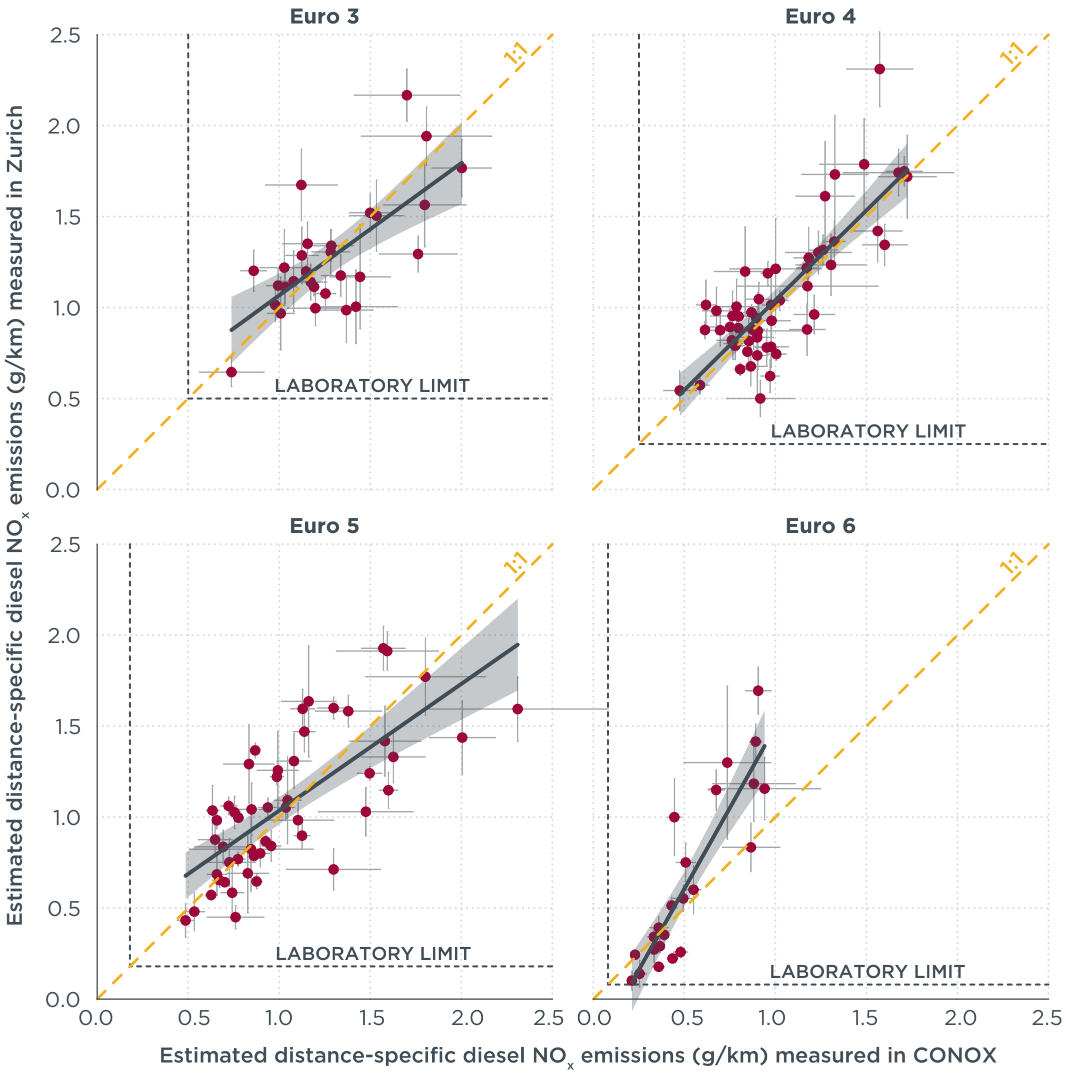

Figure 12. Comparison of average distance-specific diesel NO_x emissions in CONOX and Zurich remote sensing data. Each marker represents mean NO_x emissions of a diesel vehicle family, and whiskers represent 95% confidence intervals of the mean. Dark gray lines with shaded areas represent linear regression fits with 95% confidence intervals. Regulatory limits for laboratory tests are included for context.

Health impacts as a consequence of NO_x depend on the overall amount of emitted NO_x from each vehicle family. This is a function of the family's emissions and the distance driven by the vehicles within the family. Figure 13 plots the average distance-specific NO_x emissions, based on the Zurich remote sensing data only, and the number of vehicles on the road in Zurich for Euro 3 through Euro 6 diesel and gasoline engine families. Note that driving and ambient conditions during remote sensing measurements may not be representative of all driving in the Canton of Zurich. The size of the marker shows the annual NO_x emissions of each vehicle family estimated using annual vehicle mileage data. Annual NO_x emissions were estimated based on Zurich 2017 vehicle registrations data, aggregated to the vehicle family level and then joined with the remote sensing data and annual mileage estimates per fuel and emission standard for

Switzerland in 2017.[28] The top 10 vehicle families for each Euro standard in terms of tons of annual NO_x emissions are listed in Table 2. All such vehicle families are diesel fueled. The top 10 vehicle families in terms of estimated annual NO_x emissions across all Euro standards are labeled in Figure 13.

In terms of annual NO_x emissions, the top 10 vehicle families together account for more than one-third of total annual NO_x emissions from passenger cars estimated at 3,062 tons per year in Zurich. The highest-emitting vehicle families are almost all Euro 5 vehicles, as Euro 3 and Euro 4 vehicles are not driven as much and there were not as many Euro 6 vehicles on the road in 2017. Due to being the most common vehicle family on Zurich roads, vehicles using the 2.0-liter Euro 5 from the VW group are by far the largest annual contributor of NO_x emissions. These vehicles were part of a software recall program following the admission by the VW Group that defeat devices were installed.[29] The effectiveness of the recall in reducing real-word NO_x remains to be proven. Given the prevalence of these vehicles on the road, any change done on their real-word emissions could have a significant impact on the overall emissions from passenger cars. In total, diesel Euro 5 vehicles were estimated to account for almost half of all annual passenger car NO_x emissions, followed by diesel Euro 4 vehicles at approximately one-quarter, and Euro 6 vehicles at roughly one-eighth. These shares will change with time as the fleet in Zurich turns over.

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[28] Mario Keller et al., "HBEFA Version 3.3—Background Documentation," (Handbook emission factors for road transport, April 25, 2017), http://www.hbefa.net/e/documents/HBEFA33_Documentation_20170425.pdf; Federal Statistical Office, "Strassenfahrzeugbestand," (2018), https://www.bfs.admin.ch/bfs/de/home/statistiken/mobilitaet-verkehr/erhebungen/mfz.html.

[29] John German, VW Defeat devices: A comparison of U.S. and EU required fixes (ICCT: Washington DC, 2017), https://www.theicct.org/publications/VW-defeat-device-fixes-US-EU-comparison-dec2017.

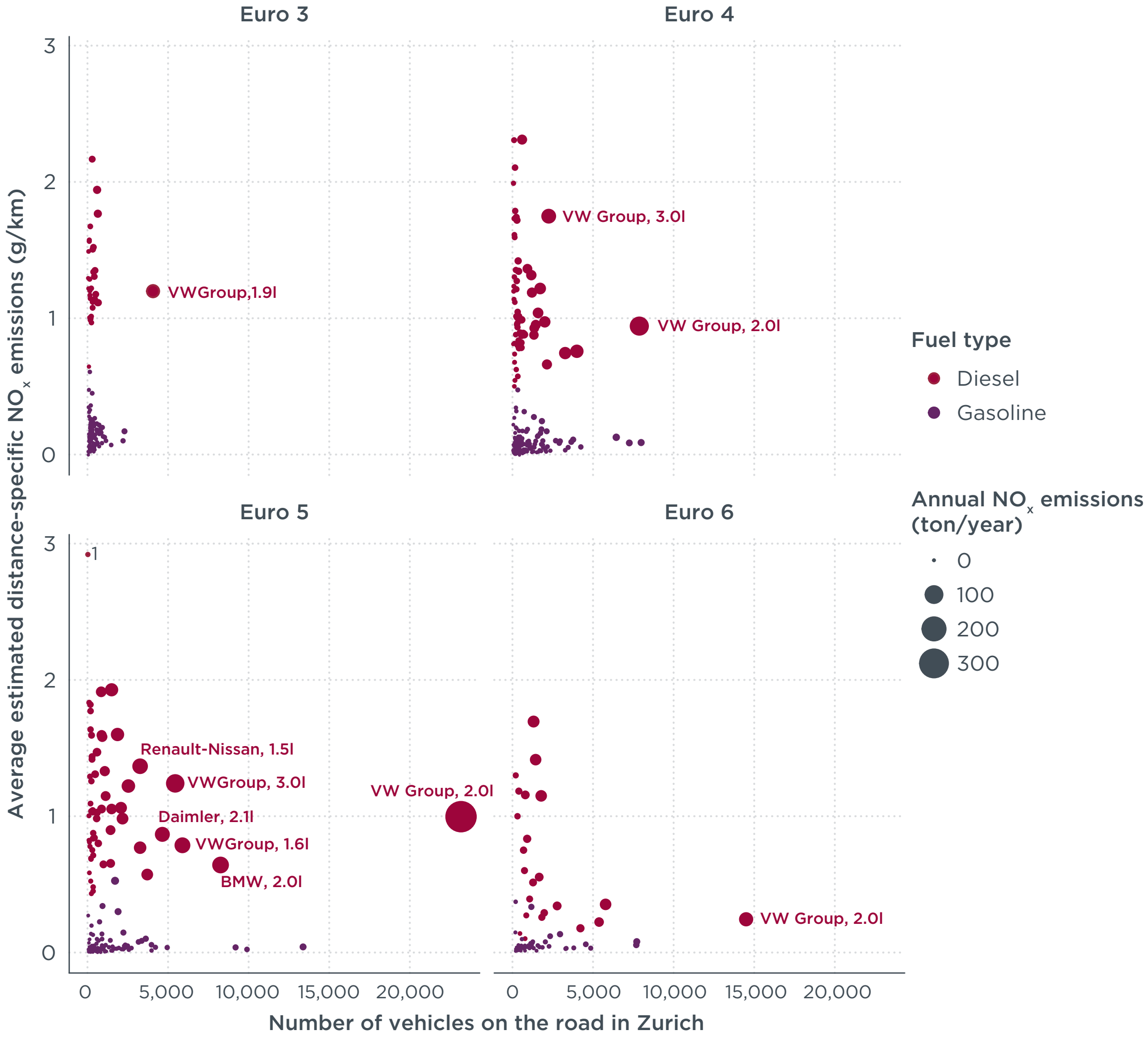

Figure 13. Mean distance-specific NO$_x$ emissions and number of registered vehicles in Zurich. Each marker represents a vehicle family. Annual NO$_x$ emissions of each vehicle family estimated using average vehicle mileage data. Top 10 vehicle families in terms of estimated annual NO$_x$ emissions across all Euro standards are labeled in the chart.

Table 2. Top 10 vehicle families per Euro standard in terms of estimated annual NO_x emissions (ton/year) in Zurich remote sensing data

Emission standard	Rank	Fuel type	Manufacturer group	Engine displacement (l)	Measurements	Fleet share	Estimated annual NO_x emissions (ton/year)
Euro 3	1	Diesel	VW Group	1.9	1,262	3.1%	47
Euro 3	2	Diesel	VW Group	2.5	156	0.5%	11
Euro 3	3	Diesel	VW Group	2.5	136	0.5%	11
Euro 3	4	Diesel	PSA Group	2	312	0.5%	7
Euro 3	5	Diesel	Daimler	2.1	159	0.5%	7
Euro 3	6	Diesel	Hyundai	2.5	129	0.2%	6
Euro 3	7	Diesel	BMW	3	196	0.4%	6
Euro 3	8	Diesel	Fiat Chrysler	1.9	159	0.4%	6
Euro 3	9	Diesel	Renault-Nissan	2.2	120	0.3%	5
Euro 3	10	Diesel	Volvo	2.4	113	0.3%	5
Euro 4	1	Diesel	VW Group	2	2,480	6.0%	112
Euro 4	2	Diesel	VW Group	3	736	1.7%	59
Euro 4	3	Diesel	VW Group	1.9	1,671	3.0%	46
Euro 4	4	Diesel	BMW	3	1,154	2.5%	37
Euro 4	5	Diesel	Daimler	3	808	1.3%	32
Euro 4	6	Diesel	Volvo	2.4	757	1.5%	29
Euro 4	7	Diesel	Daimler	2.1	589	1.2%	25
Euro 4	8	Diesel	Renault-Nissan	2	403	0.9%	23
Euro 4	9	Diesel	Ford	2	448	0.9%	22
Euro 4	10	Diesel	BMW	2	862	1.6%	21
Euro 5	1	Diesel	VW Group	2	7,767	17.5%	351
Euro 5	2	Diesel	VW Group	3	2,045	4.1%	103
Euro 5	3	Diesel	BMW	2	2,340	6.3%	80
Euro 5	4	Diesel	VW Group	1.6	2,192	4.5%	70
Euro 5	5	Diesel	Renault-Nissan	1.5	1,118	2.5%	68
Euro 5	6	Diesel	Daimler	2.1	1,471	3.5%	61
Euro 5	7	Diesel	Ford	2	872	1.9%	47
Euro 5	8	Diesel	Renault-Nissan	2	675	1.4%	45
Euro 5	9	Diesel	Hyundai	2	440	1.1%	44
Euro 5	10	Diesel	Volvo	2.4	1,007	2.5%	38
Euro 6	1	Diesel	VW Group	2	1,537	11.0%	53
Euro 6	2	Diesel	Renault-Nissan	1.6	191	1.0%	33
Euro 6	3	Diesel	Ford	2	155	1.3%	31
Euro 6	4	Diesel	BMW	2	661	4.4%	31
Euro 6	5	Diesel	Renault-Nissan	1.5	183	1.1%	31
Euro 6	6	Diesel	Daimler	2.1	803	4.1%	18
Euro 6	7	Diesel	VW Group	3	411	2.1%	14
Euro 6	8	Diesel	Hyundai	2.2	116	0.6%	14
Euro 6	9	Diesel	Mazda	2.2	215	1.3%	14
Euro 6	10	Diesel	Hyundai	2	91	0.7%	11

4. DISCUSSION AND CONCLUSION

Remote sensing data from the Canton of Zurich is unique in terms of how consistently it has been collected and the steep road grade (9%) at the main remote sensing monitoring site. The steep road grade virtually eliminates low engine load events, estimated by VSP, and skews the average engine load to a level roughly twice that of other remote sensing sites in the CONOX database. Due to the regular measurements at the same site and during the same time of the year, the Zurich data also furnish more uniform speeds and acceleration rates than the rest of the CONOX database. Despite the steep road grade, engine loads in Zurich are not excessive and remain within normal operating conditions defined in the European RDE regulation, where emission controls can reasonably be expected to operate properly.

Analyses of average NO_x emissions confirm conclusions from previous studies: Real-world emissions from gasoline vehicles are far lower than from diesel vehicles; diesel emissions are virtually unchanged from Euro 4 through Euro 5; and all Euro 3 through Euro 6 diesel vehicle families exceed laboratory limits. A comparison of the CONOX and Zurich datasets for diesel passenger cars suggests that wintertime remote sensing campaigns in the CONOX data elevated average NO_x emission levels compared with the mild temperature ranges during Zurich campaigns. However, that elevation was counteracted by the lower VSP levels in the CONOX data, which led to similar estimates of average NO_x emissions in CONOX and Zurich data. Note that the data presented in this study do not cover the most recent Euro 6 RDE compliant vehicles called “6d-TEMP,” which were introduced in September 2017. Diesel vehicles certified to Euro 6d-TEMP are expected to emit lower real-world NO_x emissions. While Euro 6 diesel vehicles do show significant reductions in average real-world NO_x emissions, Figure 12 illustrates that this is because of major emission reductions in at least half of Euro 6 vehicle families. Some Euro 6 vehicle families still emit as much NO_x as the worst Euro 5 families.

More interestingly, the higher average loads in Zurich show disparate impacts on NO_x emissions. Average gasoline NO_x emissions were lower in Zurich than for the average of the other measurement sites, suggesting that gasoline vehicles control emissions better at higher VSP levels. Euro 6 gasoline passenger cars have shown to be capable of maintaining low emission levels across a wide range of VSP. In addition, Euro 6 diesel passenger cars with low average emission levels maintained their low emissions at the higher VSP levels in Zurich. In fact, the three manufacturer groups with the lowest average diesel NO_x emissions all had lower average NO_x emissions in Zurich than at other remote sensing sites, despite VSP being twice as high in Zurich. However, as illustrated in Figure 11, diesel vehicle manufacturers with higher emissions experienced large increases in fuel-specific NO_x emissions as VSP increased. This is likely primarily related to poor emission control systems and calibration that are not robust as engine loads increase. This can occur because all vehicles in this analysis were certified under the NEDC test procedure that was focused on reducing emissions under low power demand operation. The Worldwide Harmonized Light Vehicles Test Procedure (WLTP) fully replaced the NEDC in September 2018. The WLTP requires testing at higher power demand and, in conjunction with the RDE regulation, is thus expected to lead to wider control of NO_x emissions. To the best of our knowledge, this is the first time that remote sensing data have been used to show that the relationship between NO_x and VSP varies by manufacturer group.

In terms of annual NO_x emissions in Zurich, all high-emitting vehicle families were diesel-fueled, and the majority were Euro 5 vehicles. Out of all Euro standard and fuel type combinations, diesel Euro 5 vehicles were estimated to emit almost half of annual NO_x emissions. Ten popular vehicle families, most of them Euro 5 vehicles, were estimated to account for more than one-third of passenger car NO_x emissions in Zurich while they made up approximately one-eighth of the Zurich passenger car fleet.

In summary, the comparatively high engine loads in the Canton of Zurich have helped to demonstrate the importance of appropriate emission controls during demanding acceleration events. Contrasting the Zurich and CONOX remote sensing measurements illustrates the importance of measuring emissions over a wide variety of ambient and vehicle operating conditions. Further research should attempt to disentangle driving condition, ambient condition, and instrument effects on vehicle emissions measurements in the diverse CONOX dataset.

APPENDIX: LIST OF MANUFACTURER GROUPS AND BRANDS

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

NB: Ownership structures have changed over time and continue to change.

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