Determination of real-world emissions from passenger vehicles using remote sensing data

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THE TRUE INITIATIVE

Studies have documented significant and growing discrepancies between the amount of nitrogen oxides (NO_X) emissions detected in diesel vehicle exhaust during type-approval tests and the amount that the vehicle emits in "real-world" operation—on the road, in normal driving. Excess real-world emissions are an important issue, particularly in Europe where dieselization of the light-duty vehicle fleet is much higher than in other global regions. Poor real-world NO_X emissions control has contributed to persistent air quality problems in many European cities and has adversely affected public health.

The FIA Foundation, the International Council on Clean Transportation (ICCT), C40 Cities, Global NCAP, and Transport and Environment have established The Real Urban Emissions (TRUE) Initiative. The TRUE initiative seeks to supply cities with data regarding the real-world emissions of their vehicle fleets and equip them with technical information that can be used for strategic decision-making. TRUE will use a combination of measurement techniques to produce a granular picture of the on-road emissions of the entire vehicle fleet by make, model, and model year.

TRUE is publishing a series of technical papers to document the methodologies that have been developed to evaluate real-world vehicle emissions. This is the first paper, focusing on real-world NO_X emissions measured by remote sensing. The paper details our use of remote sensing data to estimate on-road NO_X emissions from diesel and petrol passenger vehicles in Europe.

EXECUTIVE SUMMARY

High real-world vehicle emissions reflecting ineffective enforcement of Euro emissions standards have contributed to persistent air quality problems and have adversely affected public health. It is becoming increasingly apparent that more real-world data are needed to understand the impact of motor vehicles on local air quality and help policymakers develop effective policy solutions. Information on real-world emissions performance can also help consumers make informed purchasing decisions.

A few real-world emissions measurement methods exist today, each with strengths and weaknesses. Remote sensing—measuring emissions via spectroscopy as vehicles drive through a light beam—has a number of important characteristics that make it particularly beneficial for real-world emissions surveillance. Remote sensing:

- measures emissions from a large number of vehicles in a relatively short period of time, typically several thousand in a few weeks;
- can obtain a fleet-wide picture of the emissions performance of all vehicles as driven, weighted by driving activity;
- measures emissions of vehicles in-use as they are being driven;
- is non-intrusive to traffic flow and vehicle operation;
- is difficult to detect—the vehicle does not "know" it is being tested, so remote sensing is less prone to detection and circumvention;
- can monitor older as well as newer vehicles and track the effects of aging, deterioration, malfunctions, and recalls;
- is cost effective with an average cost of 1 euro per vehicle tested, which will most likely come down in the future.

This paper builds upon the CONOX remote sensing data collection and the analyses already conducted for various individual remote sensing campaigns in France, Spain, Sweden, Switzerland, and the United Kingdom between 2011 and 2017. In addition to analyzing all of the data gathered by CONOX from these individual remote sensing campaigns, there are two areas where this paper breaks new ground:

- This study documents a new method for translating fuel-specific emissions rates, or emissions in grams per kilogram of fuel burned, into distance-specific emissions rates, or emissions in grams per kilometer. This allows direct comparison of remote sensing measurements across vehicles with different fuel consumption. It also enables comparison of findings with emissions standards, chassis dynamometer testing, and portable emissions measurement systems (PEMS) testing.
- This study introduces a "vehicle family" definition and analyzes average remote sensing measurements by vehicle family. This method increases fleetwide coverage by grouping similar vehicles while continuing to separate vehicles by factors that can have a significant impact on emissions.

So far remote sensing has not been used as a tool for market surveillance in Europe. Thus, this paper goes beyond just evaluating the remote sensing data supplied by the CONOX project. To help develop remote sensing methods, this report also discusses the methods used to:

- identify required data and obtain them, such as emissions, vehicle speed and acceleration, test conditions, and vehicle information;
- validate data and exclude invalid measurements, such as engine motoring events when the engine control unit disables fuel injection as the vehicle decelerates and there are no emissions;
- conduct statistical analyses;
- establish vehicle families for data aggregation, defined as a unique combination of fuel type, Euro standard, manufacturer group, and engine displacement;
- evaluate the representativeness and biases of the data gathered;
- estimate NO_X emissions when NO_2 measurements are not available;
- calculate fuel-specific emissions values in grams per kilogram of fuel;
- convert these fuel-specific emissions values to distance-specific emissions estimates in grams/kilometer.

The CONOX dataset currently includes more than 700,000 records and is the largest database of remote sensing measurements collected across European countries. The market coverage and sample size are already impressive, and they will increase as additional remote sensing campaigns are conducted.

In the aftermath of the scandal known as "Dieselgate" publicly available PEMS testing in Europe has focused on Euro 5 and Euro 6 diesel vehicles. Remote sensing data goes well beyond this scope and allows us to evaluate vehicles back to Euro 2 and compare diesel vehicle emissions with those of petrol autos. Analyses of this data support previous findings from PEMS and remote sensing measurements about the high real-world NO_x emissions of diesel vehicles, with almost no reduction in NO_x from Euro 2 to Euro 5. This suggests that deterioration of emissions control systems over time may not be a significant factor for diesels and that improper real-world emissions calibrations are the primary problem.

On average, petrol vehicle NO_x emissions are far lower than diesel. By manufacturer group, Euro 6 petrol vehicle NO_x emissions for even the worst manufacturers were within 1.5 times the type-approval limit. For diesel vehicles, even the best manufacturer group had Euro 6 NO_x emissions of more than twice the type-approval limit, and all other manufacturer groups were at least four times the type-approval limit. Four manufacturer groups had average emissions of more than 12 times the type-approval limit.

Figure ES 1 plots the average NO_x emissions for each vehicle family, ranked from highest to lowest emissions. Diesel and petrol vehicles are plotted separately and, within each graph, vehicles are grouped by the emissions standard to which they were certified. The emissions limit for each standard is also plotted to show the proportion of families tested that meet their respective emissions limits. A separate graph at the top shows the percentage of families meeting their respective emissions limits.

Almost no Euro 3 through Euro 6 diesel vehicle family had average remote sensing measurements below their respective type-approval standards. Euro 5 diesel families performed particularly poorly: All families had NO_x emissions at least twice that of the limit, and the worst families had emissions 18 times the limit. Despite an average vehicle age of 16.4 years at the time of the

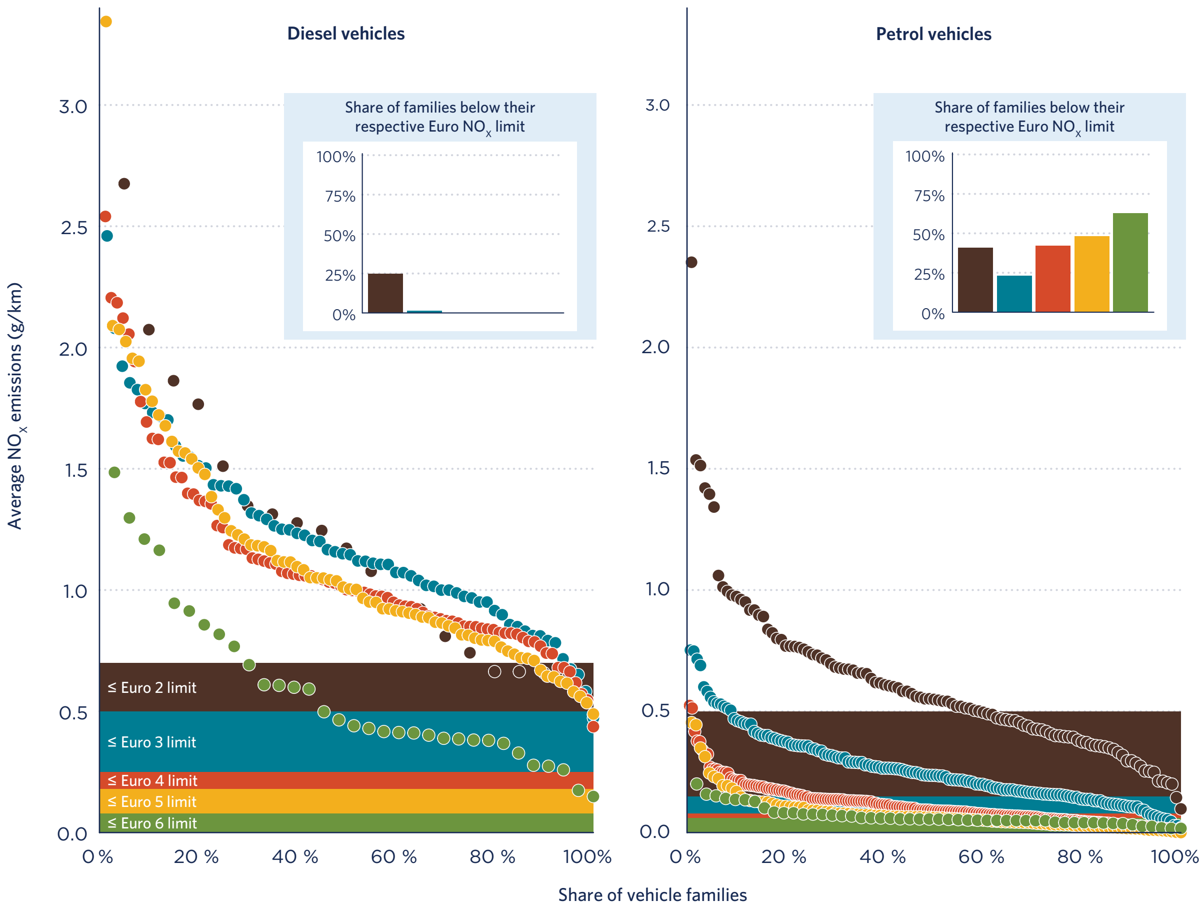

Figure ES 1: NO_x emissions (g/km) measured from remote sensing of Euro 2 to Euro 6 diesel and petrol passenger vehicles, grouped by vehicle family. Results are compared with their respective type-approval limits.

remote sensing measurements, Euro 2 vehicles actually performed better, with 25% of the families still emitting less NO_x than the Euro 2 limit.

Even though diesel NO_x limits were more than three times higher than petrol NO_x limits for Euro 3 through Euro 5, petrol vehicles performed much better, as 23% of Euro 3 petrol vehicle families had average emissions below their respective standard, ranging up to 63% for Euro 6 petrol vehicle families.

The number of petrol vehicle families with emissions below their respective limits improved as standards strengthened from Euro 3 to Euro 6, suggesting that the older petrol vehicles may have suffered from emissions control deterioration during their lifetime. While deterioration was not a focus of this study, remote sensing is well suited to track emissions of each vehicle family over time and, with additional data collection, can be used to identify deterioration.

A unique benefit of remote sensing is the ability to survey the entire market on the road, making it ideal for market surveillance. Remote sensing can reliably and cost-effectively identify the worst emitters by manufacturer, fuel type, engine type, etc. for more in-depth investigations. Member states, type-approval authorities, and research organizations can use this method to rate vehicle emissions, to identify best-in-class or worst-in-class vehicles, or as a screening tool for in-service conformity testing or defeat-device investigations.

In the EU, new Real Driving Emissions (RDE) tests are currently being phased in and a stronger type-approval framework is being put in place, but the RDE provisions in the Euro 6d-temp standard still limit the range of driving conditions and allow 2.1 times more NO_x emissions than the type-approval limit. The diesel emissions scandal underlines how reliance on a single test method is misleading and supports the need for independent and complementary testing. Remote sensing can help assess whether the implementation of these measures is successful. In addition, cities are grappling with urban air quality issues caused in large part by vehicle emissions. Remote sensing can offer these cities better data on which to make decisions about local measures, such as vehicle bans, low emissions zones, and charging fees for vehicles with higher emissions.

TABLE OF CONTENTS

ABBREVIATIONS

B7	diesel fuel containing 7% biodiesel
CH	Switzerland
CO	carbon monoxide
CO_2	carbon dioxide
E5	petrol fuel containing 5% ethanol
E10	petrol fuel containing 10% ethanol
ES	Spain
EU	European Union
FOEN	Federal Office for the Environment in Switzerland
FR	France
g/km	grams per kilometer
HC	hydrocarbon
ICCT	International Council on Clean Transportation
IVL	Swedish Environmental Research Institute
NO	nitrogen monoxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
PEMS	portable emissions measurement system
PM	particulate matter
RDE	Real Driving Emissions
RSD	remote sensing device
SE	Sweden
TRUE	The Real Urban Emissions Initiative
UK	United Kingdom

INTRODUCTION

High real-world vehicle emissions, reflecting ineffective enforcement of Euro emissions standards, have contributed to persistent air quality problems and have adversely affected public health. It is becoming increasingly apparent that more real-world data are needed to understand the impact of motor vehicles on local air quality and help policymakers develop effective solutions. Information on real-world emissions performance can also help consumers make informed purchasing decisions.

A few real-world emissions measurement methods exist today, including portable emission measurement systems (PEMS) and remote sensing. Each of these methods has its own unique strengths and weaknesses and can contribute to our knowledge of real-world emissions in different ways. One of the most important characteristics of remote sensing is its ability to measure emissions from a large number of vehicles in a relatively short period of time. To help understand how remote sensing can contribute to fleet characterization and market surveillance applications, the ICCT published a white paper in February 2018 that provides a comprehensive overview of vehicle remote sensing.[1] The paper provides technical details of the vehicle remote sensing test method, describes the multiple types of emissions analyses that can be conducted with remote sensing data, and explores areas where remote sensing can supplement emissions test methods currently used in the European Union light-duty vehicle regulatory program.

In the aftermath of the diesel emissions scandal known as "Dieselgate," the focus of this paper is on NO_X emissions. While raw data on other emissions were collected by remote sensing, in-depth analysis and validation of the hydrocarbon (HC), carbon monoxide (CO), and particulate mass (PM) data has not yet been done. We have chosen to publish the NO_X results first while continuing to work on validating results on the other pollutants.

THE USE OF REMOTE SENSING TO MEASURE REAL-WORLD EMISSIONS FROM PASSENGER VEHICLES

Chassis-dynamometer testing remains a common technique used to measure emissions levels of light-duty vehicles. The controlled conditions and repeatability of laboratory tests are essential components of determining compliance with emissions standards. But the controlled conditions also mean that laboratory testing estimates only a sliver of the conditions and vehicle emissions found in the real world. Over the past decade, PEMS were developed to directly measure on-road emissions of vehicles in broader real-life situations. But this technique is too time-consuming and expensive to be performed on a large number of vehicles.

Remote sensing technology is, in certain respects, the opposite of PEMS testing. Although limited data is collected on each vehicle, emissions from thousands of vehicles can be measured 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, but over time many hundreds or thousands of such snapshots can be collected for a given vehicle model. The aggregate result is an accurate picture of the exhaust emissions of that vehicle model over time and over a range of operating conditions. Combined with the non-intrusive nature of remote sensing, as the vehicle does not "know" it is being tested, remote sensing is a particularly good solution for market surveillance. It can quantify the emissions of individual vehicle models, evaluate the impacts of environmental and driving conditions, and track emissions deterioration over time.

This paper builds upon the CONOX[2] data collection and analyses already conducted for the various

1 Borken-Kleefeld, J. & Dallmann, T. (February 2018). *Remote sensing of motor vehicle exhaust emissions.* The International Council for Clean Transportation: Washington, DC. Retrieved from https://www.theicct.org/sites/default/files/publications/Remote-sensing-emissions_ICCT-White-Paper_01022018_vF_updated.pdf

2 The project defines CONOX as:
- **CO**mprehending **NO_x** remote sensing measuring
- **CO**mbining **NO_x** remote sensing measurements
- **CO**mparing **NO_x** real driving emissions
- **CO**llaborating on **NO_x** real driving emission measurements

individual remote sensing campaigns.[3] The primary goal is to analyze remote sensing data gathered across cities in Europe, including development of methods to standardize statistical analysis of emissions, calculate distance-specific emissions (in g/km), and evaluate emissions by vehicle family.

Despite the benefits of remote sensing and its use by emissions planners to help develop overall emissions rates, remote sensing has not usually been used by regulators as a tool for market surveillance. Thus, to help users and practitioners develop remote sensing methods and have confidence in the results, this report also discusses in detail the methods used to gather remote sensing data, validate the accuracy of the data, aggregate the data, assess sampling bias, and convert concentration measurements into distance-specific emissions. Member states, type-approval authorities, and NGOs can use these methods to help develop real-world screening tools for in-service conformity testing, defeat-device investigations, and measuring emissions system deterioration. The results will also be incorporated into the TRUE rating system to help evaluate real-world emissions by vehicle model.

REMOTE SENSING DATA SOURCES

The present study uses a dataset of more than 700,000 records supplied by the Swedish Environmental Research Institute (IVL) as part of the CONOX project. The Federal Office for the Environment in Switzerland (FOEN[4]) funded the creation of the largest database of remote sensing measurements ever collected across European countries. It represents vehicles measured in real driving conditions during campaigns carried out in France,[5] Spain, Sweden, Switzerland, and the United Kingdom between 2011 and 2017. Exhaust component concentrations measured were carbon dioxide (CO_2) nitrogen monoxide (NO), nitrogen dioxide (NO_2), carbon monoxide (CO), and hydrocarbons (HC), as well as opacity as a proxy for particulate matter (PM).

The remote sensing devices (RSDs) used were the FEAT[6] from the University of Denver and the AccuScan RSD 4600 and 5000 from Opus.[7] All of these instruments share the same measurement principle. The FEAT is a research instrument and AccuScan is its commercial version. The FEAT and the latest AccuScan 5000 can measure NO_2 as well as NO, while its former version the 4600 could measure only NO.

PROCESSING REMOTE SENSING DATA

REMOTE SENSING DATA COLLECTION

Remote sensing works by passing a light-sensing beam through the exhaust plume of a vehicle and measuring the incremental concentrations above the background level of various pollutants based on their light absorption. The measurement of all the CONOX data used here took about 0.5 second at a 100 Hz sampling rate. The result is the average over as many as 50 individual probes into the exhaust plume. A key assumption is that all gases are inert within this time scale and disperse equally and, thus, the ratio of each pollutant to CO_2 is meaningful.

At the same moment, a separate device measures the speed and acceleration of the vehicle with lasers by detecting the successive timing between the front and rear wheels. Ambient conditions are also recorded, such as ambient temperature and hygrometry. Finally, a camera takes a picture of the vehicle's license plate, which is used to acquire vehicle information. In the end, the raw data set includes:

- the concentration measurement of each emissions species relative to CO_2 above the concentration in the ambient air;
- the vehicle's speed and acceleration;
- the measurement conditions: road grade, ambient temperature and pressure, and relative humidity;

3 Borken-Kleefeld, J., Hausberger, S., McClintock, P., Tate, J., Carslaw, D., Bernard, Y., & Sjödin, Å. (2018). *Comparing emission rates derived from remote sensing with PEMS and chassis dynamometer tests.* CONOX Task 1 report. IVL Report No. C 293. Retrieved from https://www.ivl.se/english/startpage/pages/publications.html
Sjödin, Å., Borken-Kleefeld, J. Carslaw, D., Tate, J., Alt, G.-M., De la Fuente, J., Bernard, Y., Tietge, U., McClintock, P., Gentala, R., Vescio, N., & Hausberger, S. (2018). *Real-driving emissions from diesel passenger cars measured by remote sensing and as compared with PEMS and chassis dynamometer measurements.* CONOX Task 2 report. IVL Report No. C 294. Retrieved from https://www.ivl.se/english/startpage/pages/publications.html
Borken-Kleefeld, J., Bernard, Y., Carslaw, D., & Sjödin, Å. (2018). *Contribution of vehicle remote sensing to in-service/real driving emissions monitoring.* CONOX Task 3 report. IVL Report No. C 295. Retrieved from https://www.ivl.se/english/startpage/pages/publications.html

4 Federal Office for the Environment (FOEN), www.bafu.admin.ch

5 The French data in the CONOX database could not be used for this analysis, as the data were missing critical vehicle parameters needed for our analysis based on vehicle families.

6 http://www.feat.biochem.du.edu/whatsafeat.html

7 http://opusinspection.com/remote-sensing-device-technology/

- the vehicle brand, model, category, model year, body type and size, fuel type, engine size, Euro standard, type-approval CO_2 value, and empty vehicle mass. The available information can vary by jurisdiction.

EQUIPMENT CALIBRATION AND CONSISTENCY OF THE DATA SOURCE

Properly performing remote sensing measurements requires technical expertise in the setup and operation of the equipment and in the data generated by the various components of the system. The ISO 17025 standard provides guidance in properly defining the requirements. Good practices for proper remote-sensing operation include the following checks that:

- the equipment is correctly maintained and calibrated;[8]
- raw data is described with its corresponding units;
- required data post-processing is documented;
- the absence of erroneous or missing data is verified;
- a log of each measurement detailing where, when, and how it was recorded is used.

DATA VALIDATION

To accurately measure and report emissions, precautions must be taken to verify that:

- speed and acceleration were correctly recorded and are within sensible ranges;
- spectral analysis of each gas is within the equipment tolerances;
- exhaust plume size is greater than the monitoring threshold;
- there is enough time between vehicles to avoid plume cross-contamination;
- the license plate is readable;
- there is technical data available for the vehicle.

EXCLUSION OF ENGINE MOTORING EVENTS DURING DECELERATION

Remote sensing can accurately capture emissions only during events when the exhaust plume is sufficiently large. This means some exhaust gas needs to be emitted from the burning of fuel in the internal combustion engine. During vehicle deceleration, when the engine is not generating energy and is instead being "motored" by slowing down the vehicle, the engine control unit disables fuel injection and there are no emissions from the exhaust. Decelerations events can be identified for each remote sensing measurements.

Engine motoring events in the remote sensing dataset were identified using calculations of the vehicle specific power (VSP) at the wheel. VSP is calculated from vehicle speed, acceleration, the grade of the road, aerodynamic drag, and rolling resistance. Wind speed and direction as well as vehicle shape can also affect the aerodynamic drag on the vehicle and therefore VSP. Because the CONOX remote sensing campaigns were not measuring high wind speed and because aerodynamic drag is relatively unimportant except at high speeds, the VSP formula is simplified to include a generic aerodynamic drag coefficient. Generic coefficients are also used to approximate rolling resistance and the inertia of rotating masses. The simplified equation is:[9]

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

where:

- VSP is vehicle specific power in kW/ton;
- a is vehicle acceleration in m/s/s;
- v is vehicle speed in m/s;
- $slope$ is the road grade in degrees.

VSP is an excellent surrogate for engine load for remote sensing as it can be measured at the roadside, is independent of vehicle mass, and is a function of other factors influencing engine load. Note that at low deceleration rates, fuel is still injected to counter frictional losses in the drivetrain, aerodynamic and rolling resistance losses, and the power consumption of auxiliary equipment, to avoid decelerating too quickly. For typical passenger vehicles, fuel injection is disabled only when VSP is less than about -5 kW/t. Thus, remote sensing measurements with VSP less than this -5 kW/t threshold were excluded from the results.

8 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

9 Formula from the EPA guidance document (U.S. EPA, 2004) converted to the International System of Units (SI).

CALCULATING FUEL-SPECIFIC REMOTE SENSING EMISSIONS

Remote sensing measurements are reported relative to CO_2 because the optical path length of the exhaust plume is not known. But the combustion of fuel (CH_r) into carbon dioxide and water is never complete and other products are emitted such as carbon monoxide and unburned hydrocarbons. In addition, oxygen and nitrogen in the air combine at high temperature to generate nitrogen oxides.

The simplified[10] fuel combustion equation is expressed as the following:[11]

$$CH_r + m(0.21\,O_2 + 0.79\,N_2) \rightarrow$$

$$aCO + bH_2O + c(C_3H_6 + unmeasured\ C_3H_6) + dCO_2 + eNO + fNO_2 + (0.79m - (e+f)/2)N_2$$

The *a*, *b*, *c*, *d*, *e*, and *f* coefficients in the equation are determined from the concentrations of all emissions (such as CO, HC, NO, NO_2, CO_2) as measured by remote sensing equipment and reported as shown in the following example equations:

$$\frac{CO}{CO_2} = \frac{a}{d} \quad \frac{HC}{CO_2} = \frac{c}{d} \quad \frac{NO}{CO_2} = \frac{e}{d} \quad \frac{NO_2}{CO_2} = \frac{f}{d}$$

We approximate the fuel's chemical composition with an average molecular ratio of carbon and hydrogen. This ratio is considered to be 1.92 for diesel fuel, and 1.87 for petrol.[12,13]

The molecular carbon balance of the equation of combustion furnishes:

$$a + 6c + d = 1 \text{ or } d = \frac{1}{1 + CO(\%) / CO_2(\%) + 6 \times HC(\%) / CO_2(\%)}$$

For a fuel that has a generic formula of CH_r, the mass of the fuel due only to the carbon content is a fraction of the total mass of the fuel (C_{fuel}), and corresponds to:[14]

$$C_{fuel}\,(g/kg) = \frac{MC(g/mol)}{MC(g/mol) + r \times MH(g/mol)} \times 1000\,,$$

where:

- *MC* is the molar mass of carbon equal to 12 g/mol;
- *MH* is the molar mass of hydrogen equal to 1 g/mol.

The combustion equation is solved to convert the ratio of emissions to CO_2 into grams per kilogram of fuel burned. This can be done for each pollutant using its measured ratio to CO_2 and its appropriate molar mass:[15]

$$\frac{Pollutant(g)}{Fuel(kg)} = d \times \frac{MPollutant(g/mol) \times Pollutant(\%) / CO_2(\%) \times C_{fuel}}{MC(g/mol)}$$

where:

- *MPollutant* is the molar mass of the studied pollutant.[16]

The formula can be simplified to the following general form:

$$\frac{Pollutant(g)}{Fuel(kg)} = \frac{MPollutant(g/mol) \times Pollutant(\%) / CO_2(\%)}{1 + CO(\%) / CO_2(\%) + 6 \times HC(\%) / CO_2(\%)} \times \frac{1000}{MC(g/mol) + r \times MH(g/mol)}$$

After converting the emissions to CO_2 ratios using the fuel combustion equation, remote sensing provides emissions factors expressed in grams of emissions per kilogram of fuel burned.

10 The equation is a carbon balance equation that is designed for non-oxygenated liquid fuel. Diesel engine combustion with excess oxygen does not change the carbon balance of the equation, so the equation works for both non-oxygenated diesel fuel and petrol. We consider the amount of HCs in the exhaust that are not measured by the remote sensing equipment to be equal to the amount of HCs that are measured. Harley, R., Ho, J., Littlejohn, D., Singer, B., and Vo, T (1998). *Scaling of Infrared Remote Sensor Hydrocarbon Measurements for Motor Vehicle Emission Inventory Calculations,* Environmental Science & Technology, 32 (21), 3241-3248, DOI: 10.1021/es980392y.

11 FEAT Equations for CO, HC, and NO can be found here (these are equally valid for AccuScan): http://www.feat.biochem.du.edu/assets/reports/FEAT_Math_II.pdf

12 Huss, A., Maas, H., & Hass, H. (2013). *Tank-to-wheels report version 4.0; JEC well-to-wheels analysis.* Joint Research Center of the European Commission: Ispra, Italy. Retrieved from http://iet.jrc.ec.europa.eu/about-;jec/sites/iet.jrc.ec.europa.eu.about-jec/files/documents/report_2013/ttw_report_v4_july_2013_final.pdf

13 These hydrogen ratios are for non-oxygenated fuels. The hydrogen-to-carbon ratio for biodiesel varies depending on the feedstock, but in most cases a conventional B7 fuel should not cause this ratio to vary by more than a few percent. At the highest level of allowable oxygen content in E10 fuel, the carbon content would decrease by a maximum of 4%. Overall, the impact of E10, E5, and especially B7 is not huge. Also, any effect of oxygenated fuels on the calculated fuel-specific emissions values is reversed when they are converted to distance-specific values.

14 Note that CO_2 and fuel consumption are, for all practical purposes, proportional. Hence, the formulas presented here are essentially providing remote sensing emissions factors expressed in grams per kilogram of fuel burned.

15 To estimate total HC emissions, the measured ratio of HC to CO_2 needs to be multiplied by 2 to take into account HC emissions that are not measured by the remote sensing equipment.

16 NO emissions use the NO_2 molar mass since all emitted NO will eventually oxidize in the atmosphere.

AGGREGATING REMOTE SENSING DATA FOR DATA ANALYSIS

NUMBER OF REMOTE SENSING RECORDS NEEDED FOR AGGREGATE ANALYSES

A single measurement from remote sensing can give only a snapshot of the emissions levels of a vehicle at a given driving condition. Combining individual emissions measurements from remote sensing allows us to draw conclusions about the emissions performance of groups of vehicles, from large groups like all vehicles of a certain emissions standard and fuel type down to vehicle families as described in the section below.

It is important to have sufficient valid records for each vehicle group for the statistical assumptions to hold true. The central limit theorem stipulates that sample means are normally distributed around the population mean. The larger the samples, the better the so-called sampling distribution will approximate the normal distribution and enable inferences about the population mean. A rule of thumb is to assume that a sample size of 30 is sufficient for the central limit theorem to apply. To illustrate this, Figure 1 plots the means of 100 random subsamples of sizes 10, 30, and 100 randomly selected by statistical software. The figure shows that as sample size increases, the sampling distribution converges to the normal distribution. At sample size 30, the sampling distribution approximates the normal distribution reasonably well. While the 30-count cutoff is not entirely valid for all families and all circumstances, conducting more sophisticated analyses of the number of records needed would have little impact on the results. Therefore, results for groups with 30 or more measurements are presented in this report.

ESTABLISHING VEHICLE FAMILIES FOR DATA AGGREGATION

A key research goal of this report was to evaluate the use of remote sensing for market surveillance of individual vehicle models. This has not been done previously. Different ways to appropriately aggregate remote sensing measurements were evaluated for the best balance between granularity and the number of available remote sensing measurements per vehicle group.

Each vehicle model comes in hundreds of versions. They can vary by fuel type, engine power and displacement, transmission type, body styles, trim levels, and optional equipment. There are many possible ways to group these model versions. As a first step, the following attributes that potentially affect a vehicle's emissions performance were used to define different variants:

- fuel type;
- Euro standard;
- manufacturer;
- model name;
- engine displacement;
- power rating;
- transmission;
- driven wheels.

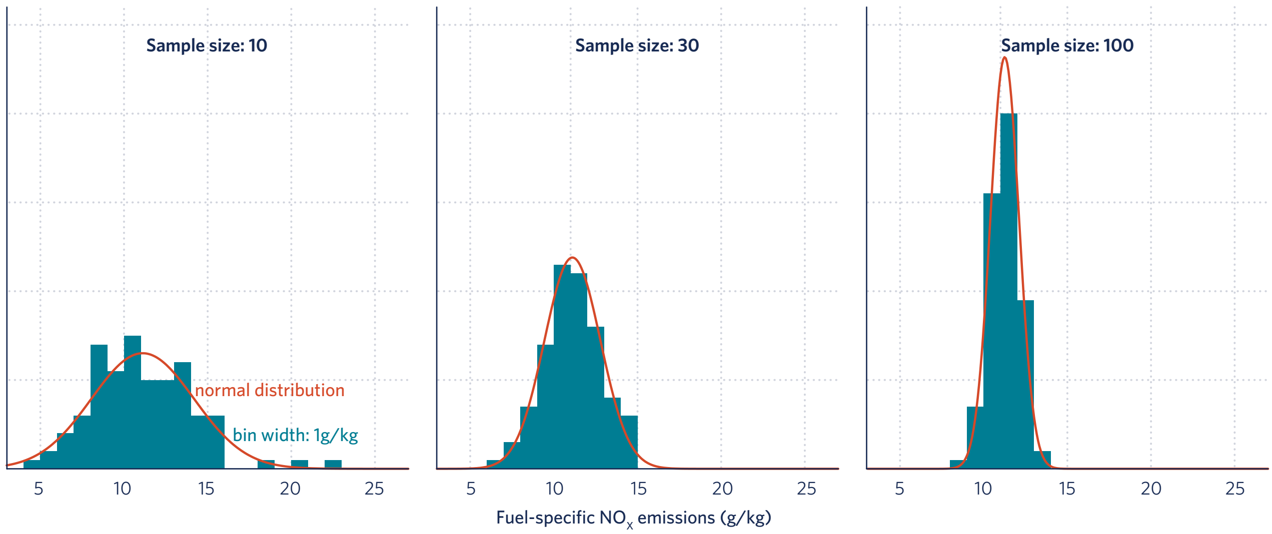

Figure 1: Sampling distribution of mean NO_x emissions of a randomly selected vehicle family for different sample sizes.

This proposed definition of a model variant can be used to estimate the number of variants that exist in the market. As a specific example, using the definition above there were many thousands of different model variants sold in the EU in 2016.[17] Figure 2 illustrates the cumulative market share that can be represented by a given number of market variants. For example, approximately 1,500 model variants can cover 90% of the market.

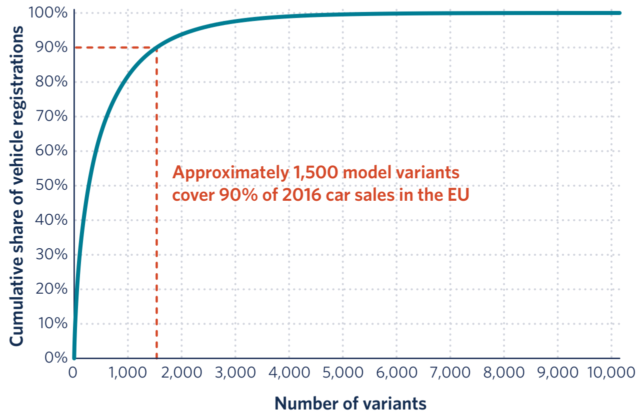

Figure 2: EU market coverage in 2016 as a function of the number of model variants.

It takes an impractically large number of remote sensing campaigns, well beyond the current deployment level of remote sensing in Europe, to be able to accurately estimate the average NO_x emissions of each model variant as defined above. This is especially true of new model variants, as the limited number of vehicles on the road makes them hard to capture. For example, the Euro 6 standard was phased in between September 2014 and September 2015, and even by 2017, fewer than 25% of measured vehicles on the road were certified to Euro 6 standards.

A better approach than trying to measure each model variant is to establish wider vehicle groups that can maximize fleet coverage while continuing to isolate the most pertinent causes of vehicles' emissions performance. To increase fleet coverage, vehicle variants were grouped into larger "families," defined as unique combinations of:

- fuel type (essentially diesel or petrol);
- Euro standard;
- manufacturer group (for example, the Volkswagen Group includes VW, Audi, SEAT, Škoda, and Porsche);
- engine displacement.

These parameters were selected for two reasons. Most importantly, the EU RDE regulation uses a set of criteria similar to this definition of vehicle family.[18] The EU regulation uses "PEMS test families" that are submitted for certification. Second, this approach is consistent with common industry practices. While it is possible for aftertreatment technology to vary for the same engine, especially for early production vehicles, manufacturers usually use the same or similar hardware and emissions control strategies in a range of vehicle models and across brands of the same group. For example, one of the Volkswagen Group defeat devices uncovered in the United States was used with the 2.0 liter diesel engine. This engine was used in a range of vehicle models from VW (Beetle, Golf, Jetta, and Passat) and in the Audi A3. In Europe, the recalled vehicles were spread across numerous manufacturers sharing the same engine type (EA189), including Audi, SEAT, Škoda, and VW.[19]

While this vehicle family concept captures the essence of how regulations and manufacturers group vehicles, we also conducted some linear regressions as a quick, ad hoc tool to provide some assurance that the grouping was sensible. As the exploratory results were extensive, they are not presented here, but the results indicated that fuel type and Euro standard were the most important predictors of emissions performance. The manufacturer of the vehicle (e.g., SEAT) or the group of manufacturers (e.g., Volkswagen Group) and the engine model (e.g., 1.6L diesel engine) were also relatively important. In comparison, the vehicle model (e.g., VW Golf, or SEAT León) was a less important regressor, providing some support that our family groupings are reasonable.

With this vehicle family definition, there were approximately 700 families sold in the EU market in 2016. Figure 3 illustrates the cumulative market share that can be represented by a given number of vehicle families. For example, only about 100 families are needed to cover 90% of the market, a dramatic reduction from the approximately 1,500 model variants needed to cover the same share.

17 Mock, P. (2017). *European vehicle market statistics. Pocketbook 2017/18.* The ICCT Europe. Retrieved from http://eupocketbook.theicct.org

18 PEMS test family groups into the same test family vehicles with the same Euro standard, propulsion type (internal combustion engine only, hybrid electric vehicle, or plug-in hybrid electric vehicle), combustion process, number of cylinders, engine displacement, fuel type, engine cooling system, engine aspiration, and exhaust aftertreatment system.

19 In some cases, the technologies cascade down through groups over time, such as from VW and Audi to Škoda and SEAT.

With this grouping methodology, more than 90% of EU car registrations from Euro 3 to 6 can be covered by monitoring around 400 families. The proposed definition of vehicle family provides a reasonable trade-off between the number of available remote sensing records for a given family and the ability to differentiate families based upon parameters that affect emissions.

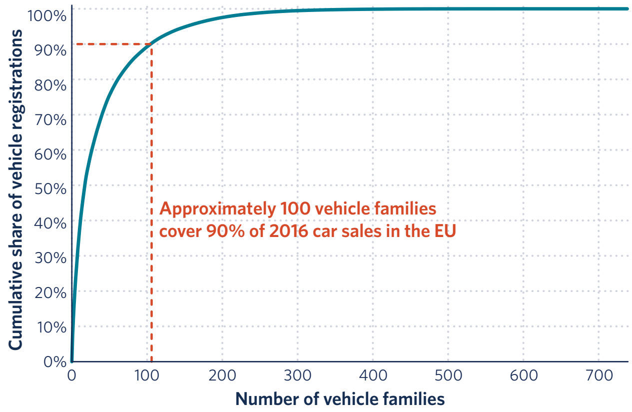

Figure 3: EU market coverage in 2016 as a function of the number of vehicle families.

NUMBER OF REMOTE SENSING MEASUREMENTS PER VEHICLE FAMILY

Figure 4 plots the distribution of the number of remote sensing measurements for each vehicle family in the CONOX database. As the database grows, so will the number of measurements for each vehicle family on the road. Vehicle family sizes, or the number of measurements per family, are binned in 500 measurement increments. We also split vehicle families with fewer than 500 measurements into bins of 30 to show the distribution of measurements at the low end of family sizes. The figure shows that vehicle families with fewer than 500 measurements account for more than one third of the measurements in the dataset.[20] However, despite skewing toward small families, families with fewer than 30 measurements account for only 3% of the dataset. In other words, the CONOX database covers 97% of all valid

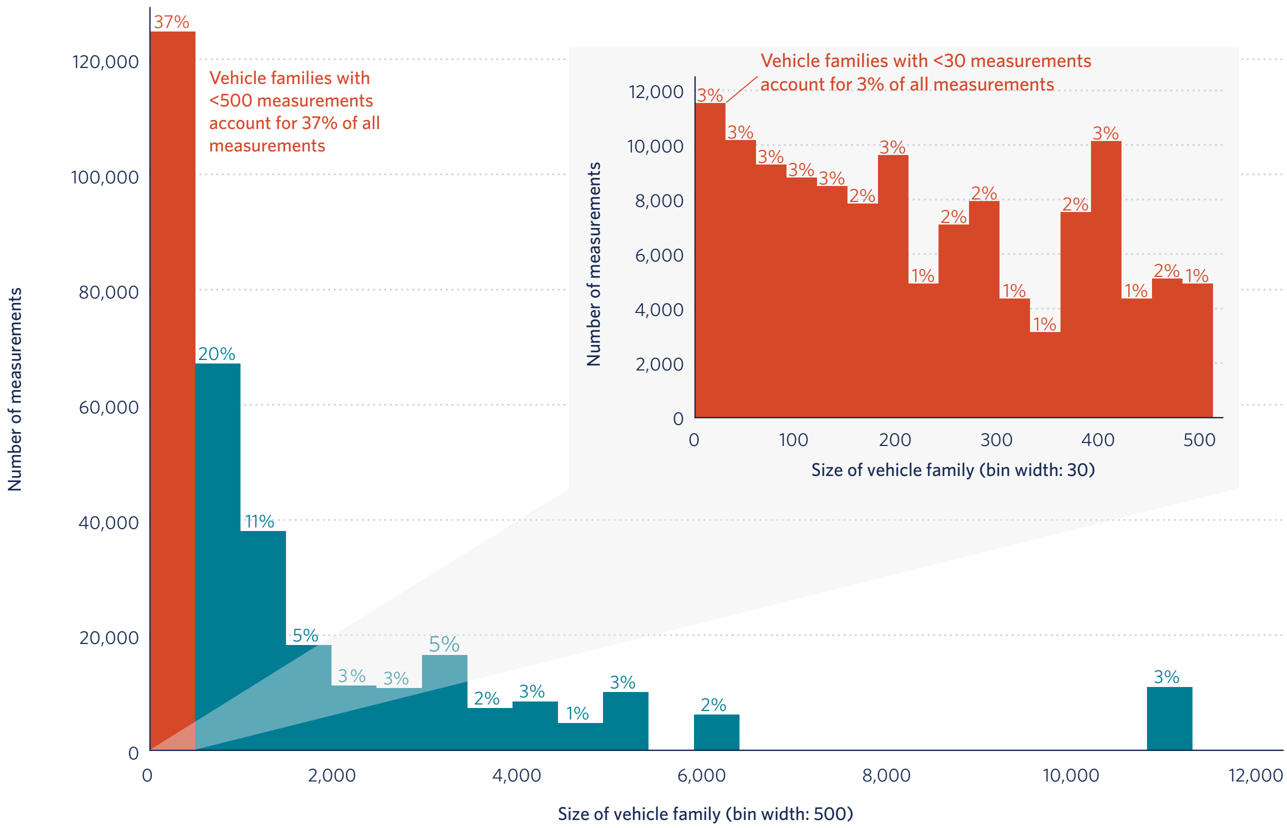

Figure 4: Distribution of the number of measurements over vehicle family size.

20 The three largest vehicle families are all from the VW group and have diesel engines:
- VWG 2.0L TDI Euro 5 (EA189 engine): 11,020 valid NO_x measurements;
- VWG 1.6L TDI Euro 5 (EA189 engine): 6,156 valid NO_x measurements;
- VWG 2.0L TDI Euro 4: 5,097 valid NO_x measurements.

measurements even after excluding vehicle families with fewer than 30 measurements.[21] In addition, for families with 30 measurements or more, we have confirmed that there is no correlation between family size and average NO_X emissions.

ANALYZING REMOTE SENSING DATA

REPRESENTATIVENESS OF REMOTE SENSING DATA

Remote sensing campaigns can cover a wide range of driving conditions that affect emissions performance. This wide coverage is a key benefit of remote sensing, and it is important to choose a variety of measurement sites to capture the whole range of driving and ambient conditions relevant for urban emissions. The CONOX dataset includes multiple conditions that varied during the remote sensing data collection. Data was collected from:

- multiple organizations using different data collection instruments;
- various countries in Europe (France, Spain, Sweden, Switzerland, and the United Kingdom);
- different locations and sites in each country, with different road gradients;
- different seasons of the year, capturing a wide range of ambient temperatures.

Remote sensing can estimate emissions under a variety of conditions, allowing an assessment of emissions by VSP, ambient temperature, and other variables. However, comparing aggregated measurements across groups of vehicles makes sense only if the driving conditions across vehicle groups are reasonably similar. Any systematic biases in driving conditions across groups could bias the emissions measurements. This section evaluates sampling biases in the CONOX data, based on vehicle attributes, driving conditions, and sampling characteristics for different emissions standards and fuel types in Table 1.

Table 1 shows that a wide range of driving conditions was captured in remote sensing measurements. The sub-samples generally have a fairly clear central tendency regarding ambient temperature, VSP, and acceleration and speed. While they do differ in some ways, such as systematically higher VSP distributions for petrol vehicles than for diesel vehicles, the differences are not large.

VSP distributions are influenced by the characteristics of the sampling sites used to collect existing data. For example, the distributions skewed toward higher VSPs all have a high proportion of data from Zurich and reflect the higher-load operating conditions typical of the Zurich sampling sites, which have a steep uphill grade. In general, there is no ideal VSP distribution. Distribution data from a single site will most likely approximate a right-skewed normal distribution (right-skewed because remote sensing biases the data toward positive VSP and because VSP was cut off at -5). It is important to (a) measure at all the driving conditions deemed of interest and (b) measure at enough sites such that the overall distribution across sites also resembles a normal distribution. That would be an indication that no individual site has a disproportionate impact on the global sample.

The three leftmost columns in Table 1 present the vehicle attributes. Each combination of emissions standard and fuel type contains several thousand valid measurements. 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 3-12 years old at the time of measurement (Euro 3 through Euro 5). The average certified CO_2 values increase with vehicle age, a result of EU-wide standards that have been driving down certified CO_2 values of new cars since 2009.

The two middle columns in Table 1 show that the share of countries and the year of data collection vary significantly by emissions standard and fuel type. For example, Spanish data made up more than half of all Euro 2 diesel vehicle measurements but accounted for less than a 10th of Euro 4 petrol vehicles. This non-uniformity results from the unique fleet characteristics in each country as well as the relatively limited number of measurement campaigns spread across seven years. Additional remote sensing campaigns will further diversify the data and improve the distribution across countries.

Despite these fluctuations in the year and location of measurements, the three rightmost columns in Table 1 illustrate that driving conditions are comparable across emissions standards and fuel types. Ambient

21 There are about 2,700 vehicle families in the CONOX database. Of these, about 1,800 had fewer than 30 measurement records. But these families with low numbers of measurements represent a small share of the overall fleet.

Fuel	Measurements	Avg. vehicle age (years)	Avg. CO_2 value (g/km, NEDC)	Ambient temperature (°C), median	VSP (kW/ton), median
Euro 2 Diesel	3,402	16.4	176	median: 21	median: 9.2
Euro 2 Gasoline	17,338	15.1	195	20.8	12.3
Euro 3 Diesel	19,702	11.6	173	20.6	9.2
Euro 3 Gasoline	31,535	11.6	184	20	10.3
Euro 4 Diesel	43,780	7.2	172	20.1	10.1
Euro 4 Gasoline	73,423	8.1	176	20.6	13
Euro 5 Diesel	57,883	3.4	150	20.3	11.1
Euro 5 Gasoline	53,797	3.6	148	20.3	13.4
Euro 6 Diesel	15,887	1.3	133	21.6	10.2
Euro 6 Gasoline	11,822	1.4	134	21.6	12.7

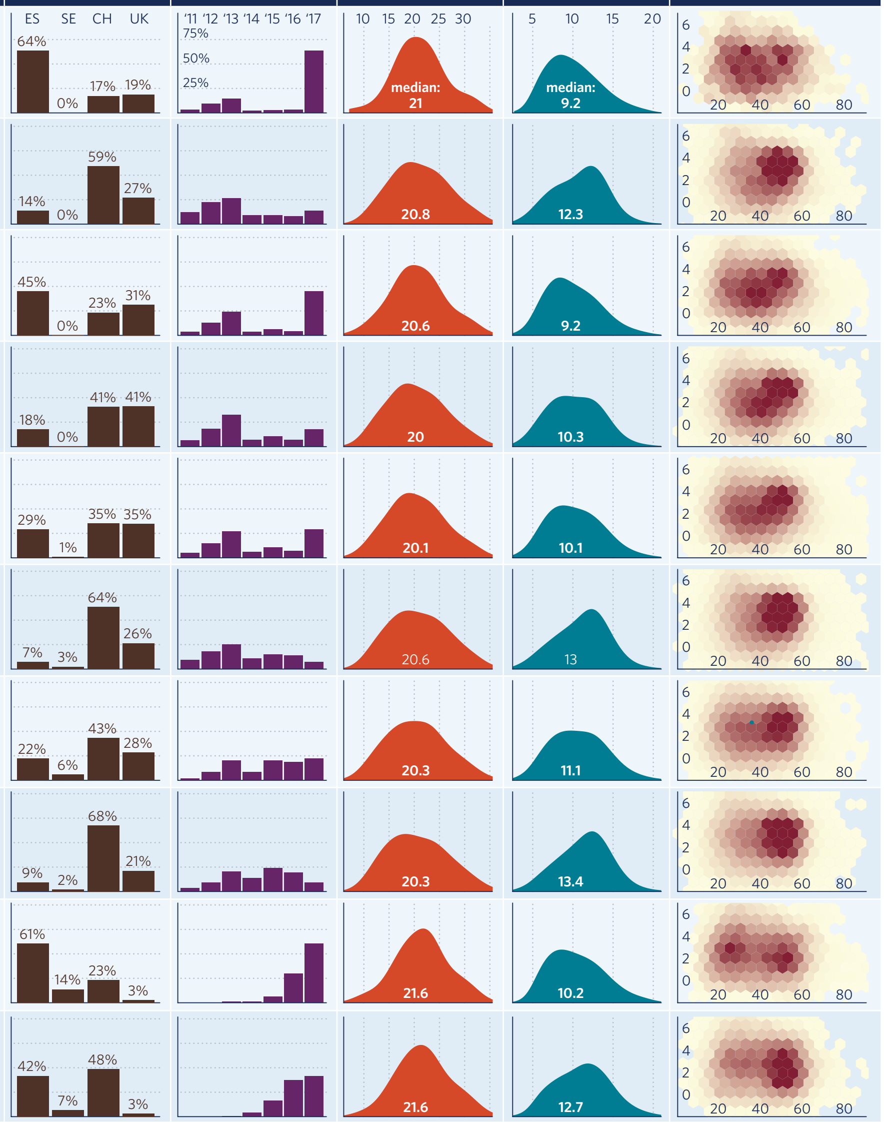

Table 1: Summary of remote sensing test conditions of Euro 2 to 6 passenger vehicles

temperature generally follows a bell-shaped distribution with the median ranging from 20–21.6°C. The distribution of VSP is less symmetrical but also has a clear central tendency with median values ranging from 9.2–13.4 kW/ton. Reflecting site characteristics such as road gradient, records from Spain and the United Kingdom tend to shift the median to the left, while the Swiss data have the opposite effect, explaining why the distribution is somewhat asymmetrical. Lastly, the heat maps of vehicle acceleration[22] on the y-axis over speed on the x-axis indicate that the large majority of vehicles across all groups were measured at a speed between 20 and 60 km/h and accelerating with 1 to 5 kilometers per hour per second (km/h/s). Virtually all vehicle groups center around 50 km/h and 3 km/h/s, indicating the

22 For a better comparison between sites, the acceleration takes into account the vehicle's longitudinal acceleration and the gravitational component due to uphill driving.

absence of significant biases related to vehicle speed and acceleration.

For comparison with the acceleration/speed distributions in Table 1, Figure 5 contains graphs of the acceleration versus speed distributions for three laboratory tests and the remote sensing data distributions from the whole CONOX database.[23] The NEDC was the test cycle used for type approval prior to September 2017. Note that this test mostly consists of cruises with zero acceleration and, even when accelerations are encountered, they are very mild. The NEDC is currently being phased out and replaced with the WLTC for type-approval tests. Accelerations on the WLTC are more frequent and faster than on the NEDC but are still mild compared with data from remote sensing. The Artemis cycles are not type-approval test cycles but are frequently used for evaluations because they were developed to represent real-world driving patterns.[24] The urban version of this test shows a larger coverage of higher acceleration rates than the other cycles shown but still excludes the higher acceleration rates and more transient driving that occur in the real world.

Excluding the NEDC, which is not representative of the range of typical real-world driving, the majority of driving on the rest of the tests occurs at speeds between 20 and 60 km/h and with 1 to 5 km/h/s acceleration, similar to the acceleration versus speed distributions from remote sensing. Except for the lack of data above 110 km/h, the remote sensing data appears to cover the range of typical real-world driving.

There are some potential limitations of remote sensing that should be kept in mind when analyzing data and designing a remote sensing campaign. First, it is challenging for some remote sensing technology to collect data at highway speeds above 100 km/h because a single lane of travel in each direction is required for cross-road sampling and higher speeds are generally limited to roadways with multiple lanes of traffic. Second, it is not typical to measure cold start emissions using remote sensing, although remote sensing instrumentation could be set up at the exit of a long-term parking facility to investigate cold start emissions. Third, it is necessary to have a significant number of remote sensing records to piece together an

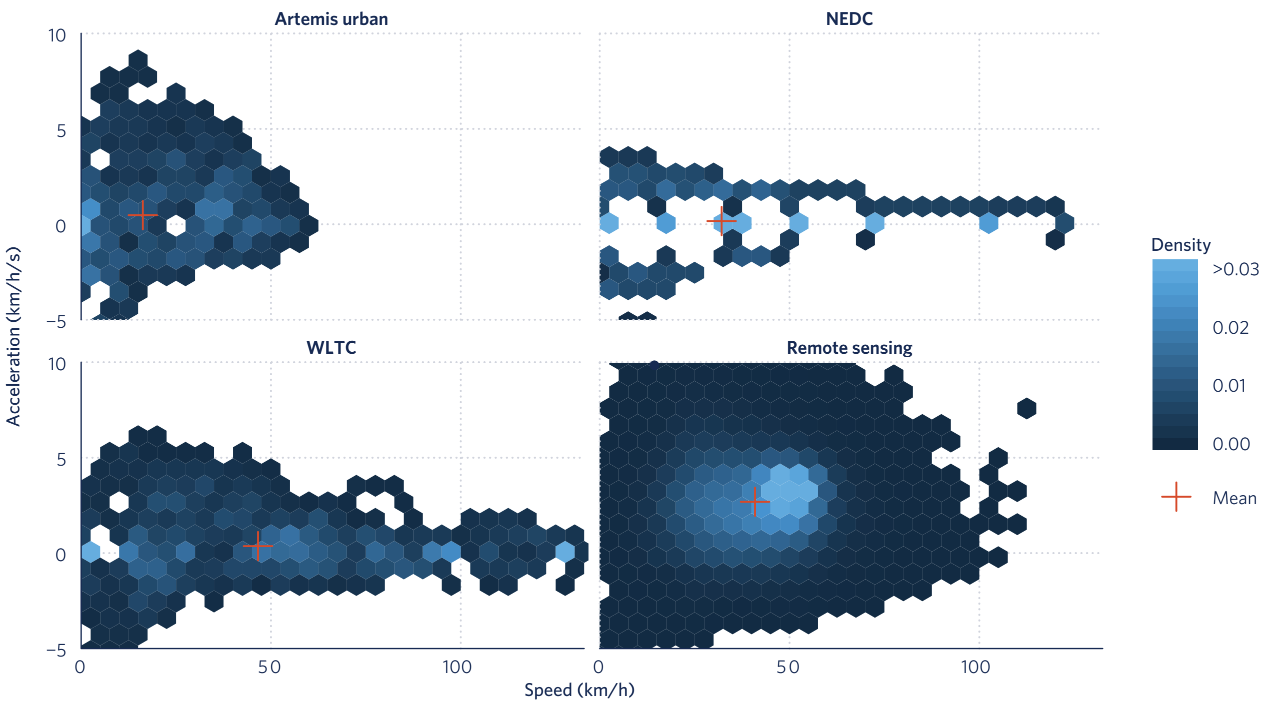

Figure 5: Comparison of speed versus acceleration over different cycles and for remote sensing measurements. Crosses denote the mean speed and acceleration.

23 For consistency with the remote sensing data, VSP measurements less than -5 kW/t were also removed from the laboratory tests.

24 For information on the Artemis driving cycle, see https://www.dieselnet.com/standards/cycles/artemis.php

accurate picture of a given vehicle group's emissions levels. And fourth, it is not possible to collect emissions data during vehicle idling or at low vehicle speeds, below about 5 km/h. It is possible to overcome all except for the last with careful design and more data, while, except during heavy congestion, emissions during idle are normally a small portion of overall emissions.

IMPACT OF VSP AND AMBIENT TEMPERATURE ON FUEL-SPECIFIC NO_X EMISSIONS FACTOR

While there are multiple real-world variables that influence the fuel-specific NO_X emissions factor (g NO_X/kg fuel burned) of a specific vehicle, two of the most important are VSP and ambient temperature.

Figure 6 investigates the relationship between VSP and NO_X emissions in Euro 6 vehicles. The brown bars in the upper graph show that the fuel-specific NO_X emissions factor for Euro 6 diesel vehicles is lowest at a VSP between 3 kW/t and 8 kW/t, but increases below and above, with a very pronounced increase at a VSP above 26 kW/t. The increase below 3 kW/t is probably caused by a reduction in CO_2 concentrations with lower load for diesel engines, thus increasing the fuel-specific NO_X emissions factor. However, there is no technical reason why the fuel-specific NO_X emissions factor should increase above 8 kW/t for diesel vehicles. The reason for this observed behavior could potentially be due to the fact that the NEDC test is designed to focus on reducing emissions under low power demand operation and less so under higher power demand. A VSP of 26 kW/t approximately corresponds to the maximum VSP peaks encountered during the NEDC test cycle.

The lower graph in Figure 6 shows the VSP distribution measured in the remote sensing tests. This graph illustrates the relative amount of driving associated with each of the VSP bins in the upper graph. As already

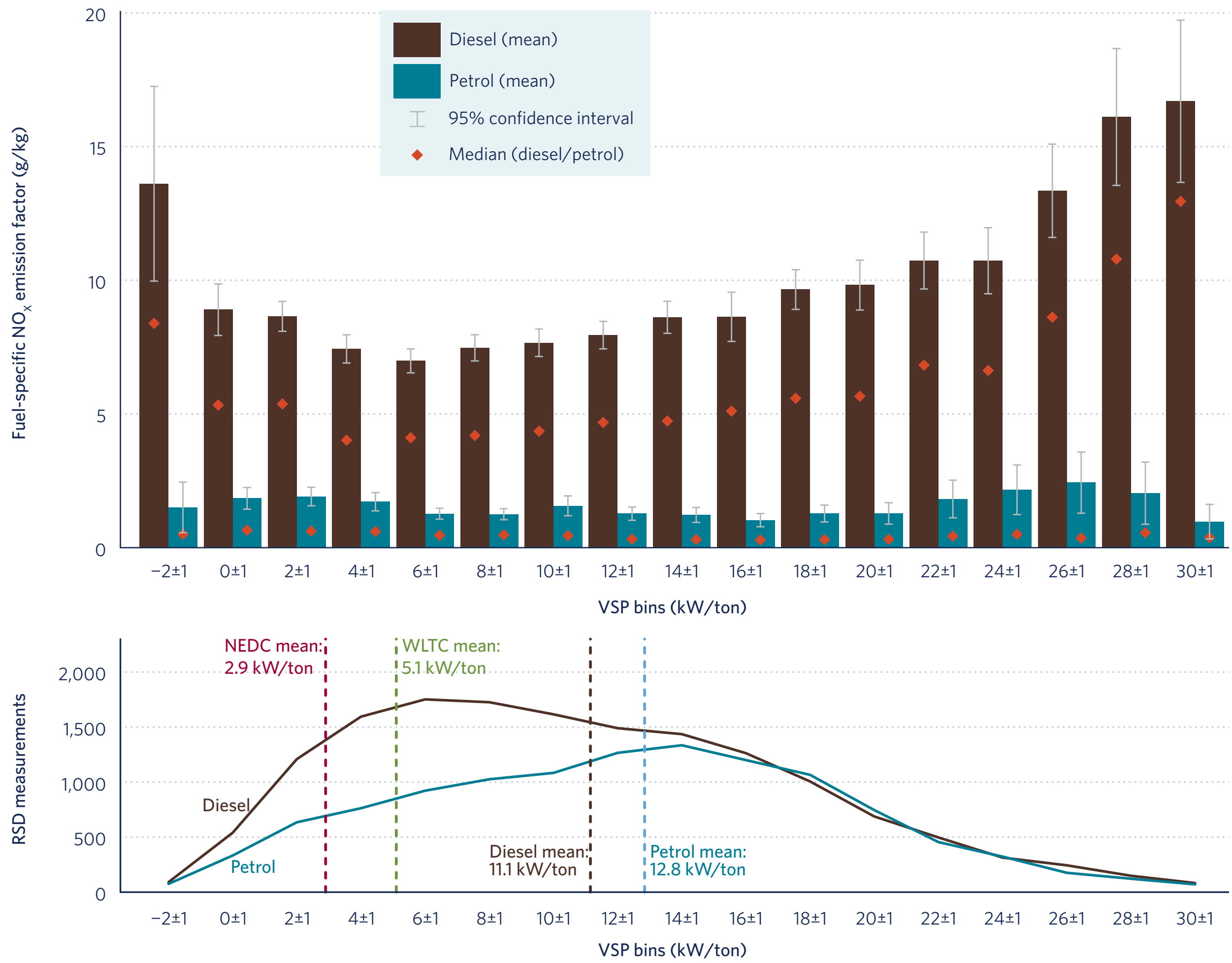

Figure 6: Top graph: Fuel-specific NO_X emission ratio over VSP bins for Euro 6 diesel and petrol vehicles. Bottom graph: number of measurements per VSP bin for Euro 6 diesel and petrol vehicles

indicated in Table 1, diesel vehicles were generally measured at lower power demand than petrol vehicles. This is due to a much larger proportion of the Euro 6 diesel testing having been conducted in Spain over congested city conditions (see Table 1), limiting VSP.

The blue bars in Figure 7 show that the fuel-specific NO_x emissions factor for Euro 6 petrol passenger vehicles is much lower than for diesel passenger vehicles and is also much less affected by VSP. There is little change in the fuel-specific NO_x emissions factor at low loads, or low VSP bins, which may be because CO_2 concentration levels of petrol engines remain higher at low loads and tend to be constant as long as the engine is powering the vehicle. The fuel-specific NO_x emissions factor does increase somewhat at higher loads, but not until above 22 kW/t.

Note the very large differences between the median and the mean fuel-specific NO_x emissions factor for Euro 6 petrol cars. This indicates that there are a small number of petrol measurements that have very high emissions. Examination of the data suggests this is true of most vehicle families.

The different remote sensing campaigns in the CONOX database cover a wide range of VSP, up to at least 30 kW/ton, and therefore gives us the ability to evaluate vehicle emissions over widely differing driving conditions. However, when comparing aggregated results, the average measured VSP should correspond to normal VSP engine operation. An average VSP below 3 kW/t is considered to be too lenient, as it matches the average VSP conditions encountered during the NEDC. An average VSP above 20 kW/t is considered to be too dynamic, as it corresponds to the 95th percentile of VSP for the WLTC. Analyses performed later in this paper were evaluated to ensure that each vehicle family was, on average, measured within these boundary conditions.

Figure 7 investigates the relationship between ambient temperature and NO_x emissions in Euro 6 vehicles. The brown bars in the upper chart show that the fuel-

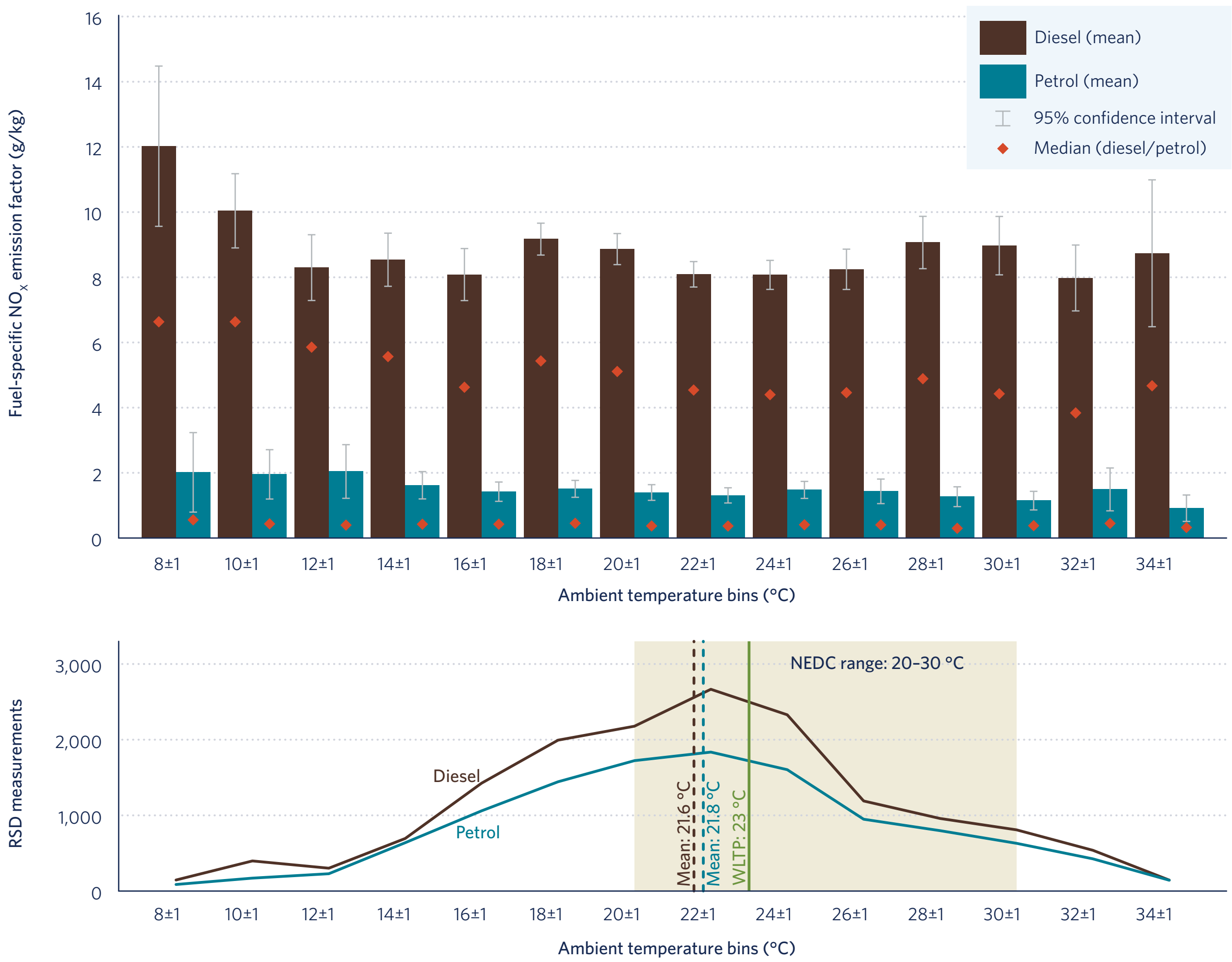

Figure 7: Top graph: Fuel-specific NO_x emissions ratio over ambient temperature bins for Euro 6 diesel and petrol vehicles. Bottom graph: Ambient temperature distribution of Euro 6 diesel and petrol vehicles.

specific NO_x emissions factor for Euro 6 diesel passenger vehicles is much higher than for petrol cars, represented by the blue bars, at all ambient temperatures. Ambient temperature also has a larger impact on diesel than on petrol vehicles. Petrol vehicles have reasonably steady fuel-specific NO_x emissions factors at all temperatures, while diesel vehicles have significant increases below 12°C. Note that 8°C–10°C are not prohibitively low ambient temperatures and should not require any modification of the combustion process or affect engine power output. Thus, these increases below 12°C can be reasonably explained only by alternative emissions strategies applied by manufacturers in some conditions outside the type-approval tests.

The lower graph in Figure 7 shows the ambient temperature distribution for the remote sensing measurements. This graph illustrates the relative amount of driving associated with each of the ambient temperature bins in the upper graph. The distributions range from about 8°C to 34°C, with most of the measurements made from about 14°C to 30°C. They are reasonably similar for diesel and petrol vehicles.[25] Median and mean temperatures are both about 22°C, indicating little skew in the distribution, and are within type-approval conditions of 20°C–30°C.

The different remote sensing campaigns in the CONOX database covered ambient temperatures from approximately 0°C to 44°C, giving us the ability to evaluate vehicle emissions over widely differing ambient conditions. However, when comparing any kind of aggregated results, the average measured ambient temperature should be in a range that corresponds to the typical temperature range across Europe, or between 0°C and 30°C.[26] Analyses performed later in this paper were evaluated to ensure that each vehicle family was, on average, measured within these boundary conditions.

ESTIMATION OF NO_X EMISSIONS WHEN NO_2 MEASUREMENT IS NOT AVAILABLE

NO_x refers to NO and NO_2 emissions. Between the two, NO is the major gas emitted from internal combustion engines, although NO_2 is still a substantial contributor to NO_x emissions. The AccuScan RSD 4600 remote sensing unit, used for certain campaigns before 2016, measured only NO emissions.

When NO_2 was not available in the remote sensing data, NO_x emissions were calculated using the NO measurement and an estimate of the NO_2 to NO_x ratio. Table 2 presents results from the CONOX remote sensing campaigns when NO and NO_2 analyzers were used simultaneously to calculate the NO_2 to NO_x ratio.

The ratio varies primarily according to the Euro standard for diesel vehicles. The introduction of diesel oxidation catalysts with Euro 2 and NO_x after-treatment systems with Euro 6 have increased the formation of NO_2 in the tailpipe. The calculated NO_2 ratios should be updated as more remote sensing data is gathered. It may also be more appropriate to have separate ratios for SCR and LNT NO_x aftertreatment systems once more Euro 6 data is available, although this would require collecting new information to identify the type of aftertreatment system.

NO_2 emissions from petrol vehicles are difficult to measure because of their low concentration levels. The FEAT system used for some of the remote sensing campaigns has a dedicated measurement channel for NO_2,[27] which demonstrated that the ratio of NO_2 to NO_x can vary from 0.6–8.4% for petrol vehicles. We chose to use a fixed ratio of 5% for all petrol vehicles. In the future, uncertainties related to NO_2 emissions will be reduced because of the increased availability of instruments measuring NO_2.

NO_2 to NO_x Ratio (%)	Diesel	Petrol
Euro 1	22%	5%
Euro 2	16%	5%
Euro 3	22%	5%
Euro 4	32%	5%
Euro 5	30%	5%
Euro 6	35%	5%

Table 2: NO_2 to NO_x ratio per fuel type and Euro standard. For diesel vehicles, ratios were calculated from the data, whereas a constant, average value was assumed for petrol vehicles from Carslaw & Rhys-Tyler (2013) data.

25 Remote sensing campaigns were usually performed during summer months, when dry weather is more likely and conditions are more amenable for operators working by the road all day.

26 The RDE regulation defines the 0°C to 30°C range as moderate ambient temperature.

27 Carslaw, D., & Rhys-Tyler, G. (2013, December). New insights from comprehensive on-road measurements of NO_x, NO2 and NH3 from vehicle emission remote sensing in London, UK. *Atmospheric Environment, 81, 339-347.* Retrieved from https://www.sciencedirect.com/science/article/pii/S1352231013007140

ESTIMATION OF DISTANCE-SPECIFIC NO_X EMISSIONS

All passenger vehicles with the same fuel type and Euro standard are required to meet the same distance-specific emissions limit, measured in g/km, for NO_X and other pollutants. Because these limits are set independently of each vehicle's fuel consumption, fuel-specific emissions in g NO_X/kg of fuel burned are not sufficient to compare vehicles' real-world performance with type-approval limits. Similarly, comparisons across vehicles are fairer when considering distance-specific emissions. For example, vehicles using less fuel and emitting less CO_2 will, all else being equal, have a higher NO_X to fuel ratio. A direct comparison of fuel-specific emissions would disfavor vehicles emitting low levels of CO_2 and reward vehicles with high CO_2 emissions.

To address this problem, a novel method for converting fuel-specific to distance-specific emissions was developed and evaluated. This is a new conversion that, to the best of our knowledge, has not previously been conducted. It significantly improves the usefulness of remote sensing data.

The first step was to estimate the average distance-specific CO_2 value of each vehicle family as follows:

- The type-approval CO_2 value of each sampled vehicle was retrieved using the license plate information.
- The average type-approval CO_2 value was calculated for each vehicle family.
- The type-approval values were corrected for real-world CO_2 emissions, using estimates of the gap between real-world and type-approval CO_2 values, as summarized in Table 3.[28]

The amount of CO_2 emitted per unit of mass fuel burned is proportional to the amount of carbon in the fuel per unit of mass. This varies for different fuels, simplified previously as CH_r, and can generalized as the following:

$$\frac{CO_2\,(kg)}{fuel\,(kg)} = \frac{MCO_2(g/mol)}{MC(g/mol) + r \times MH(g/mol)},$$

where:

- MCO_2 is the molar mass of CO_2 equal to 44 g/mol.

28 Tietge, U., Mock, P., German, J., Bandivadekar, A., & Ligterink, N. (2017, November 5). *From laboratory to road: A 2017 update of official and 'real-world' fuel consumption and CO_2 values for passenger cars in Europe.* The ICCT: Washington, DC. Retrieved from http://theicct.org/publications/laboratory-road-2017-update

CO_2 gap (%)	Diesel	Petrol
Euro 1	0%	0%
Euro 2	10%	10%
Euro 3	15%	13%
Euro 4	22%	22%
Euro 5	30%	26%
Euro 6	39%	33%

Table 3: Relative difference between real-world and manufacturers' type-approval CO_2 emissions values per Euro standard and fuel type.

Table 4 summarizes the factors used for conversion from fuel to CO_2 for diesel and petrol fuel.[29] The factors in Table 4 are for non-oxygenated fuels. Results of pollutants reported in grams per kilogram of fuel burned are overestimated when vehicles use oxygenated fuels, by up to 4% for E10 and by approximatively 1% for B7.[30] However, converting emissions into distance-specific values reverses the oxygenated fuel impact on fuel-specific emissions, discussed above, so results reported in grams per kilometer should be largely unaffected by oxygenated fuels.

The conversion back to a measure relative to the mass of CO_2 is necessary to use remote sensing data in combination with CO_2 type-approval values. These conversions make the reasonable assumption that CO_2 is the main product of fuel combustion during the type-approval test. Mass emissions of other combustion products—HC and CO—are limited and therefore neglected for this conversion.

Fuel type	kg of fuel to kg of CO_2
Diesel	3.16
Petrol	3.17

Table 4: Conversion factor from a kilogram of fuel to a kilogram of CO_2.

Distance-specific pollutant emissions are calculated based on the average fuel-specific emissions factor, the carbon content of fuel, and the type-approval CO_2 value for each family, corrected by the average real-world CO_2 gap. This results in an estimate of average pollutant emissions in grams per kilometer for each vehicle family:

29 Huss et al., 2013.

30 The CO_2 emissions factor for E10 reported in Huss et al. (2013) is 3.04, or about 4% lower than petrol, and 3.13 for B7, or about 1% lower than diesel fuel.

$$\text{pollutant}\left(\frac{g}{km}\right) = \text{mean}\left(\frac{\text{pollutant}\ (g)}{\text{fuel}\ (kg)}\right) \times \frac{\text{fuel}\ (kg)}{CO_2\ (g)} \times \text{mean}\ CO_2\left(\frac{g}{km}\right) \times (1 + CO_2\ \text{gap}\ (\%))$$

Note that this equation assumes that distance-specific CO_2 emissions during each remote sensing measurement are always equal to the distance-specific CO_2 value during the type-approval test adjusted for the real-world gap. In reality, CO_2 emissions are a function of the load on the vehicle and vary widely across in-use conditions. Thus, while the next section validates that the average distance-specific pollutant emissions estimates calculated using this method are likely to be representative, caution should be used when applying the conversion to individual remote sensing records.

RESULTS: REMOTE SENSING MEASUREMENTS OF NO_X EMISSIONS FROM PASSENGER VEHICLES

As discussed in the introduction, due to concern with real-world diesel NO_X emissions this paper focuses on the NO_X results while work continues on validating the other pollutant results.

NO_X COMPARISON BETWEEN REMOTE SENSING AND PEMS FOR EURO 5 AND 6 DIESEL PASSENGER VEHICLES

Over the last two years, hundreds of on-road tests using PEMS have been conducted in Europe. The remote sensing data analyzed in this report was compared with PEMS results conducted by government authorities in France, Germany, the Netherlands, and the U.K. and by Environmental Action Germany (Deutsche Umwelthilfe) on 541 Euro 5 and Euro 6 diesel passenger vehicles.[31]

Figure 8 compares the average fuel-specific NO_X emissions results for all Euro 5 and Euro 6 diesel vehicle families with both remote sensing and PEMS measurements. For the PEMS data, fuel-specific NO_X emissions were calculated using the reported CO_2 emissions. The results are almost identical for both Euro 5 and Euro 6 diesels, indicating good agreement between the remote sensing and PEMS data despite the very different data collection methods.

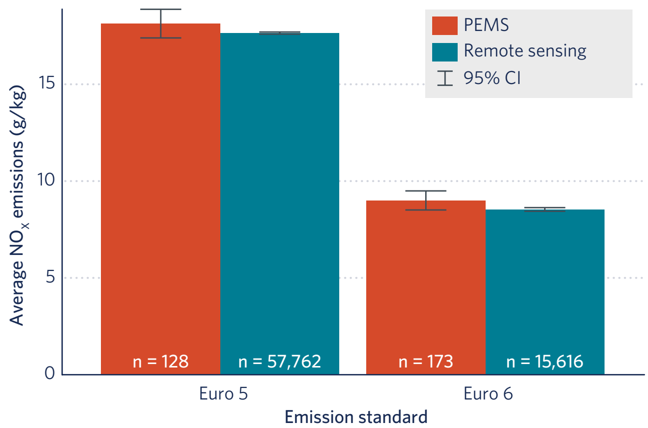

Figure 8: Average diesel fuel-specific NO_X emissions factor (g/kg) from emissions testing campaigns with PEMS and remote sensing.

Using the previously described method to convert remote sensing data to distance-specific emissions values, Figure 9 compares the remote sensing and PEMS results in g/km for Euro 5 and Euro 6 diesel vehicles. Again, the results are almost identical,[32] suggesting that the method of converting remote sensing data from fuel-specific to distance-specific values is reasonably accurate for average emissions.

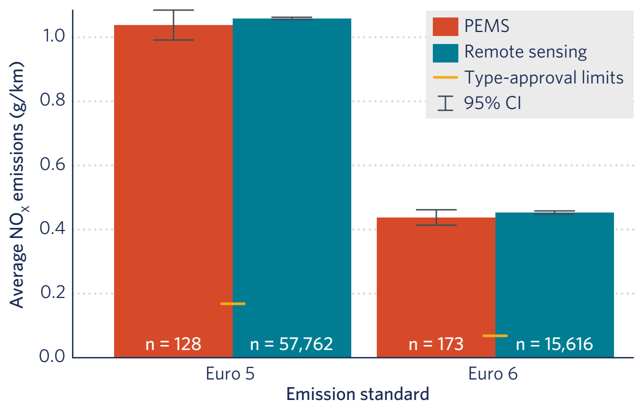

Figure 9: Average diesel NO_X emissions (g/km) measured from emissions testing campaigns with PEMS and calculated from remote sensing data. (Corrected on 6/6/2018 to fix Y axis incorrectly labeled as g/kg)

31 Baldino, C., Tietge, U., Muncrief, R., Bernard, Y., & Mock, P. (2017). *Road tested: Comparative overview of real-world versus type-approval NO_x and CO_2 emissions from diesel cars in Europe.* The ICCT: Washington, DC. Retrieved from https://www.theicct.org/sites/default/files/publications/ICCT_RoadTested_201709.pdf

32 The much smaller confidence interval for remote sensing data is due to the much larger sample size.

The advantage of converting emissions to distance-specific values is that the results can be compared directly to type-approval limits. The results in the rest of this section will therefore be presented in g/km.

NO_x RESULTS FROM EURO 1 TO EURO 6

Figure 10 summarizes remote sensing NO_x emissions for diesel and petrol vehicles from Euro 1 to Euro 6. What is immediately apparent is that NO_x emissions from petrol vehicles have decreased proportionally to reductions in the type-approval limit, while real-world diesel NO_x emissions have remained almost unchanged from Euro 1 through Euro 5. In fact, petrol vehicles certified to Euro 3 and produced between 2000 and 2005 perform much better than Euro 6 diesel vehicles produced from 2014 onward. The remote sensing data confirms the extremely high level of NO_x emissions from diesel vehicles compared with type-approval limits and that the ratio of real-world emissions to the type-approval limit increased as the limits were reduced.

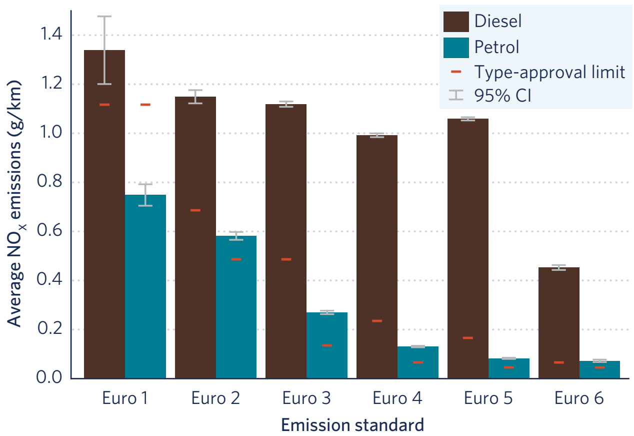

Figure 10: Overview of NO_x emissions (g/km) of the on-road fleet, from Euro 1 to Euro 6, for petrol and diesel passenger vehicles.[33]

Measurements of pre-Euro 5 vehicles might capture the deterioration of emissions control and aftertreatment systems. For example, NO_x emissions of Euro 3 petrol vehicles with an average age of 11.6 years significantly exceed the type-approval limit, most likely reflecting a drop in efficiency of their three-way catalysts because of deterioration.

Although we do not present an analysis of emissions control system deterioration in this paper, this is an important topic for future analyses. Remote sensing is particularly well suited for investigating deterioration as ample data is available for most vehicle families and was measured over a number of years.[34]

RESULTS PER MANUFACTURER GROUP FOR EURO 6 VEHICLES

Figure 11 summarizes average NO_x emissions by car manufacturer group for Euro 6 petrol and diesel vehicles.

Petrol vehicle NO_x emissions varied considerably from manufacturer to manufacturer, but even the worst manufacturers were within 1.5 times the Euro 6 type-approval limit. Manufacturers are already in a good position to comply with the new RDE limit of 0.126 g/km for petrol passenger vehicles.

Diesel NO_x emissions also varied considerably by manufacturer and at much higher levels. Even the best manufacturer group, Jaguar Land Rover, had average emissions of more than twice the type-approval limit. All other manufacturer groups emitted more than four times the type-approval limit. The four worst groups—Suzuki, Subaru, Fiat Chrysler Automobiles, and Renault-Nissan—had average emissions 12 times the type-approval limit.

RESULTS FOR EURO 6 VEHICLES BY MODEL YEAR

Figure 12 illustrates average NO_x emissions for Euro 6 petrol and diesel vehicles for model years 2014–2017. NO_x emissions from petrol vehicles were stable across model years and were below the type-approval limit. NO_x emissions from diesel vehicles were well above both the Euro 6 type-approval limit and the on-road conformity factor set by the RDE test procedure for Euro 6d-temp, although emissions declined each model year.

The average reduction of approximately 0.2 g/km in diesel NO_x emissions from 2014 to 2017 is interesting, especially as none of the measured vehicles were RDE-compliant. It is possible that this development was caused by manufacturers progressively adopting more robust emissions control systems to meet the Euro 6d-temp limit that has been in force since September 2017.

33 Note: For Euro 1 and 2, the limit refers to NO_x+HC limit.

34 Borken-Kleefeld, J., & Chen, Y. (2015, January). New emission deterioration rates for gasoline cars—results from long-term measurements. *Atmospheric Environment,* 101, 58–64. Retrieved from https://doi.org/10.1016/j.atmosenv.2014.11.013
Chen, Y., & Borken-Kleefeld, J. (2016, March 19). NO_x emissions from diesel passenger cars worsen with age. *Environmental Science & Technology* 50 (7), 3327–3332. Retrieved from https://doi.org/10.1021/acs.est.5b04704

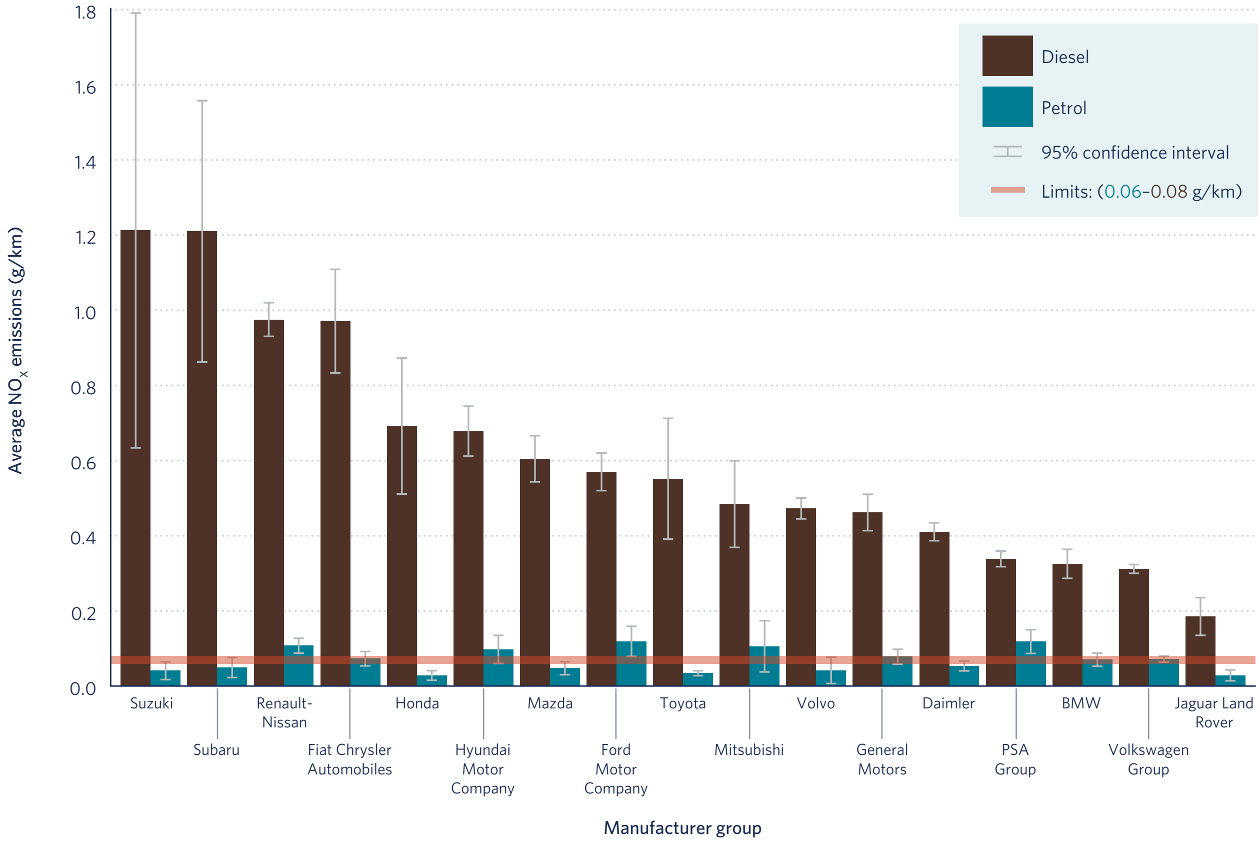

Figure 11: Overview of NO_x emissions (g/km) of the Euro 6 fleet per manufacturer group, for petrol and diesel passenger vehicles.

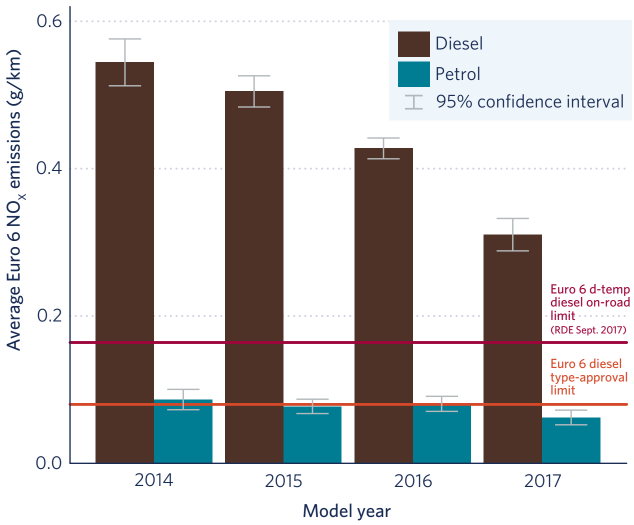

Figure 12: NO_x emissions (g/km) from Euro 6 vehicles for model years 2014–2017. Note: The Euro6-temp limit for petrol is lower than for diesel (0.126 g/km)

RESULTS FROM EURO 2 TO 6 BY VEHICLE FAMILY

Previous findings in this report—by fuel type, Euro standard, model year, and manufacturer group—are novel in the sense that they present distance-specific estimates that can be compared with type-approval limits. In addition, this study introduces the vehicle family concept to remote sensing, which turns remote sensing into a valuable screening tool for regulators and researchers.

Figure 13 plots the average NO_x emissions of each vehicle family, ranked from highest to lowest. Diesel and petrol vehicles are plotted separately, and, within each graph, vehicle families are grouped by the emissions standard to which they were certified. The emissions limit for each standard is also plotted to show the proportion of families tested that meet their respective emissions limits. A separate graph at the top shows the percentage of families meeting their respective emissions limits.

Although not entirely unexpected given the high average real-world diesel NO_x emissions, it is still striking to see that almost no Euro 3 through Euro 6 diesel vehicle family had average remote sensing measurements below their respective type-approval limits. Euro 5 diesel families performed particularly poorly, as all families had NO_x emissions at least twice the limit and the worst families had emissions 18 times the limit. Note that the best Euro 4-6 diesel families emitted roughly as much NO_x as the worst petrol families.

Euro 2 diesel vehicles, despite being on the road for an average of 16.4 years, actually performed better, with 25% of the families still having average emissions below the Euro 2 limit. In fact, while NO_x emissions from Euro 2 diesels were on average higher than for petrol Euro 2 vehicles, some Euro 2 petrol families recorded levels as high as diesel vehicles. In addition, the data show almost no improvement in average diesel NO_x emissions as the emission limits were lowered from Euro 2 to Euro 5. This suggests that deterioration of the emissions control system over time may not be a significant factor for diesel vehicles and that improper real-world emissions calibrations are the primary problem.

Petrol vehicles performed much better, especially considering that diesel NO_x standards were more than three times higher than petrol NO_x limits for Euro 3 through Euro 5. More than half of all petrol pre-Euro 6 vehicle families exceeded their respective limits. But petrol vehicles showed important improvements under successive Euro standards, with 23% to 63% of families having average real-world emissions below their respective limits. Note that the number of families with emissions below the limits improved as standards strengthened from Euro 3 to Euro 6, suggesting that the older petrol vehicles may have suffered from emissions control deterioration (after-treatment, or in-cylinder control) by the time of the measurement.

These results are particularly interesting for market surveillance because they help identify high-emitting vehicle families for further investigation. Even for diesel vehicles, where almost all vehicle families exceeded type-approval limits, the results can help agencies target the worst performers.

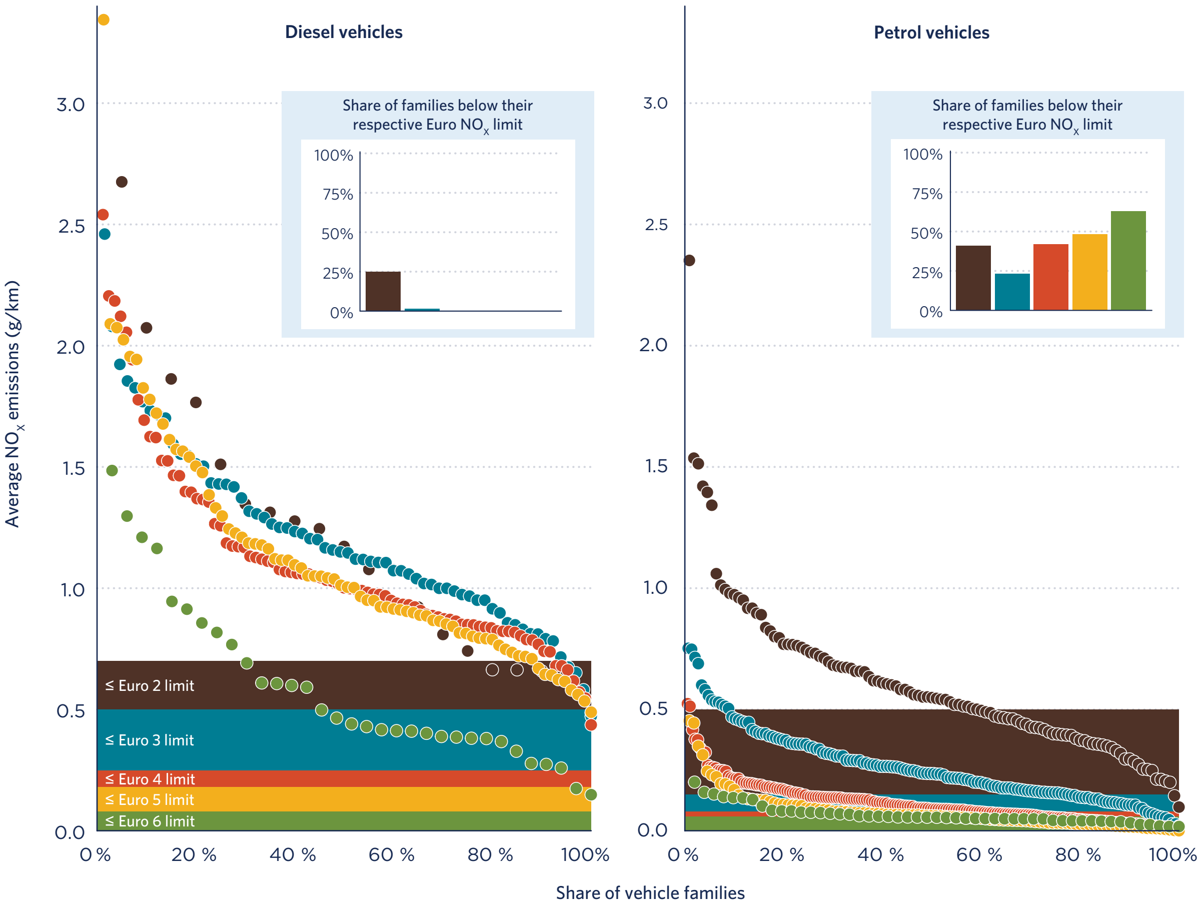

Figure 13: NO_x emissions (g/km) measured from remote sensing of Euro 2 to Euro 6 diesel and petrol passenger vehicles, grouped by vehicle families. Results are compared with the respective type-approval limits.

Manufacturer Group	Fuel type	Engine size (l)	# PEMS tests by Member states (and others)	# RSD records	Average NO_x —PEMS (g/km)	Average NO_x —RSD (g/km)	Average/ min/max ambient temperature —PEMS (°C)	Average/ min/max ambient temperature —RSD (°C)
Fiat Chrysler Automobiles	Diesel	2	2	52	1.06	1.49	8.4 / 5.0/10.5	21.8/ 12.3/32.5
Hyundai Motor Company	Diesel	2.2	12	80	0.31	1.3	23.1/ 20.9/25.3	21.7/ 9.0/34.2
Subaru	Diesel	2	0 (1)	48	1.13	1.21	Unknown	21.3/ 10.1/33.2
Renault Nissan	Diesel	1.6	10	351	0.99	1.16	5.2/ 3.0/12.0	21.9 / 7.5/36.9

Table 5: List of the four highest NO_x emitting Euro 6 vehicle families as measured by remote sensing, compared with PEMS results.

USING REMOTE SENSING RESULTS TO IDENTIFY HIGHEST EMITTERS AND COMPARISON WITH PEMS INQUIRIES

As illustrated in Figure 13, the estimation of NO_x emissions from each vehicle family can identify worst performers. As one specific example, Table 5 shows the four highest-emitting Euro 6 vehicle families as measured by remote sensing, all emitting more than 12 times the Euro 6 type-approval limit. Table 5 compares results from remote sensing and PEMS tests. For three of the four highest emitters, on-board measurement and remote sensing agree reasonably well. Both indicate that NO_x emissions were more than 10 times higher than the Euro 6 type-approval limit.

Even though more than 200 diesel vehicles were tested with PEMS equipment in the aftermath of Dieselgate, none of them measured the Subaru vehicles equipped with the 2.0L diesel engine.[35] The CONOX remote sensing database measured this Subaru 48 times and identified it as the third-highest NO_x emitter of all Euro 6 vehicle families.

PEMS measurements for the 2.2L diesel engine from Hyundai Kia did not match remote sensing results, even though a reasonable number of PEMS measurements—12—were conducted during Dutch emissions inquiries. One possible cause of this difference might be test conditions. PEMS tests performed by the Netherlands were all conducted at ambient temperatures between 20.9°C and 25.3°C, which falls within the type-approval requirements. Many manufacturers have acknowledged that they reduce the efficacy of NO_x reduction outside that temperature range. The 80 remote sensing measurements for this vehicle family found high levels of NO_x across three countries (Spain, Sweden, and Switzerland), and spanned temperatures from 9°C to 34°C.

CONCLUSIONS

The methods used to gather and analyze remote sensing data discussed in this report build upon previous studies. In addition to evaluating all of the CONOX remote sensing data from measurement campaigns in Spain, Sweden, Switzerland, and the United Kingdom from 2011 to 2017, there are two areas where this report breaks new ground:

- This study develops a new method for translating fuel-specific emissions rates in grams per kilogram of fuel burned into distance-specific emission rates in grams per kilometer. This allows direct comparison of remote sensing measurements across vehicles with different fuel consumption values and with emission standards, chassis dynamometer testing, and PEMS testing.
- This study introduces and defines the "vehicle family" concept and analyzes average remote sensing measurements by vehicle family. Using this approach, remote sensing can reliably and relatively cheaply single out worst emitters by manufacturer, fuel type, engine type, etc. for more in-depth

35 A German car magazine was the first to measure a Subaru 2.0L diesel vehicle with PEMS. Investigators found NO_x emissions of more than 14 times the Euro 6 type-approval limit, in line with the remote sensing results: https://www.auto-motor-und-sport.de/test/nox-abgastests-realbetrieb-strassenverkehr-neuwagen-testverfahren/

investigations of defeat devices, deterioration effects, and malfunctions.

Remote sensing has a number of important characteristics that make it a particularly good tool for market surveillance, including measurements of a large number of vehicles in a relatively short period of time, emissions measurements of in-use vehicles as they are being driven, non-intrusiveness to traffic flow and vehicle operation, and the ability to monitor older as well as newer vehicles, at relatively low cost.

The CONOX dataset currently includes more than 700,000 records and is the largest database of remote sensing measurements collected across European countries. The market coverage and sample size will increase as additional remote sensing campaigns are conducted.

Results from these data echo findings from PEMS testing and other remote sensing studies about the high real-world NO_x emissions of diesel vehicles, with almost no reduction in NO_x emissions levels from Euro 2 to Euro 5 diesel vehicles. Publicly available PEMS data predominantly cover Euro 5 and Euro 6 diesel vehicles, but remote sensing data go well beyond this range and allow us to evaluate vehicles as old as Euro 2, as well as compare diesel with petrol vehicle emissions.

On average, petrol vehicle NO_x emissions are far lower than diesel vehicle emissions. In addition, a much larger share of petrol vehicles emit NO_x levels on par with or below their respective standards, even considering that diesel NO_x limits were more than three times higher than petrol NO_x limits for Euro 3 through Euro 5. In fact, almost no Euro 3 through Euro 6 diesel vehicle family had emissions below the respective type-approval limits, while 23% to 63% of petrol vehicle families had average emissions below their respective limits.

By manufacturer group, Euro 6 petrol vehicle NO_x emissions for even the worst manufacturers were within 1.5 times the type-approval limit. For diesel vehicles, even the best manufacturer group had NO_x emissions more than double the type-approval limit; vehicles of all other manufacturer groups emitted levels at least four times the type-approval limit; and four manufacturers' vehicles had average emissions of more than 12 times the type-approval limit.

The number of petrol vehicle families with average emissions levels below their respective limits improved as standards strengthened from Euro 3 to Euro 6, suggesting that the older petrol vehicles may have suffered from emissions control deteriorations during the measurement campaign. While deterioration was not a focus of this study, remote sensing is well suited to track emissions of each vehicle family over time and, with additional data collection, can be used to identify deterioration.

In the EU, new RDE-based emissions standards are being phased in, and a stronger type-approval framework is being put in place. But the RDE provisions in the Euro 6d-temp standard still limit the range of driving conditions and allow 2.1 times more NO_x emissions than the type-approval limit. The diesel emissions scandal underlines how reliance on a single test method is misleading and the need for independent and complementary testing. Remote sensing can reliably survey the entire market on the road at reasonable cost, making it an ideal method to assess whether the implementation of RDE-based standards and other measures is successful. In addition, cities are grappling with urban air quality issues caused in large part by vehicle emissions. Remote sensing can offer these cities better data on which to make decisions about local measures, such as vehicle bans, low emissions zones, and charging fees for vehicles with higher emissions.

APPENDIX

NO_x emissions for Euro 6 vehicle families with 30 or more measurements are listed below:

Fuel type	Manufacturer group	Engine displacement (l)	Number of measurements	Average NO_x emissions (g/km)	95% confidence interval (g/km)[36]
Petrol	Fiat Chrysler Automobiles	0.9	102	0.017	-0.032–0.066
Petrol	PSA Group	1.6	30	0.017	0.001–0.033
Petrol	BMW	4.4	122	0.019	0.001–0.038
Petrol	Toyota	1.5	171	0.025	0.013–0.038
Petrol	Toyota	1.8	670	0.026	0.019–0.032
Petrol	Daimler	4.7	74	0.032	0.002–0.063
Petrol	Volkswagen Group	3.6	53	0.037	0.02–0.054
Petrol	Daimler	1	99	0.038	0.025–0.05
Petrol	Ford Motor Company	1.5	84	0.039	0.025–0.054
Petrol	Daimler	1.6	445	0.041	0.022–0.059
Petrol	Mazda	1.5	45	0.041	0.018–0.063
Petrol	Toyota	1	93	0.041	0.023–0.059
Petrol	PSA Group	1	44	0.041	-0.002–0.084
Petrol	BMW	2	614	0.043	0.027–0.059
Petrol	Volkswagen Group	1.8	392	0.049	0.023–0.075
Petrol	Subaru	2	53	0.049	0.021–0.078
Petrol	Hyundai Motor Company	1.2	162	0.049	0.036–0.062
Petrol	Renault-Nissan	1.6 (1,618 cm^3)	83	0.05	0.029–0.07
Petrol	Volvo	2	72	0.05	0.003–0.096
Petrol	Daimler	3	130	0.05	-0.004–0.104
Petrol	Hyundai Motor Company	1	69	0.05	0.031–0.069
Petrol	Volkswagen Group	1.2	897	0.051	0.043–0.059
Petrol	Suzuki	1.6	84	0.052	0.017–0.086
Petrol	Mazda	2	135	0.053	0.03–0.077
Petrol	Ford Motor Company	1.2	123	0.054	0.037–0.072
Petrol	Toyota	2.5	146	0.055	0.029–0.082
Petrol	Toyota	1.2	33	0.056	0.016–0.096
Petrol	Volkswagen Group	3	80	0.056	0.024–0.089
Petrol	Fiat Chrysler Automobiles	1.4	193	0.057	0.044–0.069
Petrol	Hyundai Motor Company	1.4	51	0.057	0.003–0.11
Petrol	Toyota	1.3	66	0.059	0.012–0.106
Petrol	Daimler	2	388	0.06	0.038–0.082
Petrol	General Motors	1.4 (1,364 cm^3)	204	0.061	0.034–0.087
Petrol	BMW	3	168	0.062	0.004–0.12
Petrol	Renault-Nissan	0.9	172	0.068	0.042–0.094
Petrol	Volkswagen Group	1.4	891	0.07	0.053–0.086
Petrol	Renault-Nissan	1.6 (1,598 cm^3)	38	0.072	0.033–0.111
Petrol	Fiat Chrysler Automobiles	1.2	329	0.075	0.063–0.087

36 The lower bound of the confidence interval is negative in a few cases. This can occur for two reasons. First, negative lower bounds can be artifacts of reporting two-sided confidence intervals based on the Student's t-distribution and can occur in subsamples with low means, high variance, and/or few observations. Because these errors were relatively rare and minor, canonical confidence intervals were reported rather than using other lesser-known methods that avoid implausible bounds (e.g., certain bootstrapping methods). Second, it is possible to have negative emissions readings when the pollutant level in the exhaust's plume is lower than ambient air level. This means that the emissions control system is actually cleaning up the air, which is currently rare but is likely to increase as emissions standards become more stringent.

Fuel type	Manufacturer group	Engine displacement (l)	Number of measurements	Average NO_x emissions (g/km)	95% confidence interval (g/km)[36]
Petrol	Hyundai Motor Company	1.6	144	0.076	0.045-0.107
Petrol	Renault-Nissan	1	31	0.077	0.027-0.126
Petrol	General Motors	1.4 (1,398 cm^3)	241	0.081	0.056-0.107
Petrol	Volkswagen Group	1	699	0.081	0.067-0.096
Petrol	Daimler	0.9	110	0.084	0.016-0.153
Petrol	Volkswagen Group	2	652	0.102	0.071-0.132
Petrol	PSA Group	1.2	637	0.128	0.093-0.164
Petrol	BMW	1.5	125	0.135	0.064-0.206
Petrol	General Motors	1	55	0.136	0.028-0.245
Petrol	Renault-Nissan	1.2	302	0.141	0.104-0.178
Diesel	Jaguar Land Rover	2	171	0.149	0.111-0.187
Petrol	BMW	1.6	163	0.151	0.072-0.231
Petrol	Renault-Nissan	1.1	75	0.158	0.077-0.24
Diesel	BMW	3	556	0.174	0.067-0.281
Petrol	Ford Motor Company	1	198	0.2	0.115-0.286
Diesel	Jaguar Land Rover	3	36	0.259	0.162-0.356
Diesel	Volkswagen Group	2	2,610	0.274	0.258-0.289
Diesel	Volkswagen Group	1.4	388	0.278	0.246-0.31
Diesel	PSA Group	1.6	1,361	0.328	0.306-0.35
Diesel	Volkswagen Group	1.6	1,242	0.368	0.347-0.389
Diesel	Ford Motor Company	1.5	395	0.38	0.337-0.423
Diesel	Daimler	3	611	0.381	0.34-0.423
Diesel	PSA Group	2	298	0.386	0.335-0.437
Diesel	BMW	2	1,032	0.389	0.357-0.42
Diesel	Daimler	2.1	1,294	0.402	0.373-0.431
Diesel	BMW	1.6	50	0.411	0.283-0.538
Diesel	BMW	1.5	161	0.413	0.342-0.483
Diesel	Volkswagen Group	3	407	0.417	0.363-0.47
Diesel	Hyundai Motor Company	1.6	99	0.429	0.352-0.507
Diesel	Volvo	2	1,055	0.44	0.412-0.469
Diesel	General Motors	1.6	405	0.465	0.416-0.514
Diesel	Hyundai Motor Company	1.7	272	0.498	0.437-0.56
Diesel	Mazda	2.2	404	0.592	0.532-0.651
Diesel	Volvo	2.4	270	0.599	0.521-0.677
Diesel	Toyota	1.6	51	0.607	0.433-0.781
Diesel	SsangYong Motor Company	2.2	33	0.609	0.43-0.789
Diesel	Honda	1.6	89	0.692	0.511-0.873
Diesel	Fiat Chrysler Automobiles	1.6	90	0.768	0.644-0.892
Diesel	Daimler	1.5	83	0.818	0.675-0.96
Diesel	Ford Motor Company	2	262	0.857	0.758-0.955
Diesel	Renault-Nissan	1.5	1,074	0.914	0.866-0.961
Diesel	Hyundai Motor Company	2	90	0.946	0.738-1.153
Diesel	Renault-Nissan	1.6	351	1.164	1.055-1.273
Diesel	Subaru	2	48	1.21	0.862-1.558
Diesel	Hyundai Motor Company	2.2	80	1.298	1.037-1.558
Diesel	Fiat Chrysler Automobiles	2	52	1.485	1.142-1.829

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For details on the TRUE rating and related questions, contact Rachel Muncrief, **rachel@theicct.org**. For more information on the TRUE project, visit **www.trueinitiative.org**.

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