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Contribution of vehicle remote sensing to in-service/real driving emissions monitoring - CONOX Task 3 report

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Preface

Understanding real driving (or on-road or real-world) emissions is crucial for taking cost-effective actions to reduce air pollution and improve air quality in urbanized areas all over the world. Remote sensing represents one means to monitor real driving emissions from large on-road fleets, and has been used in Europe in various applications already since the early 1990's to reach a better understanding of the European situation regarding real driving emissions. However, until present remote sensing has never been used in Europe for e.g. legislative or enforcement purposes, which instead have relied on other emission measurement approaches, providing results that are more or less representative for real driving emissions (e.g. chassis dynamometer or PEMS testing, idle tests). In light of "dieselgate", approaches capable of measuring the "real" real driving emissions, such as remote sensing, have gained an increasing interest, also for emission control purposes.

This report presents the outcome of a common European and US collaborative effort to analyse how large datasets from remote sensing measurements carried out in various locations and countries across Europe could be used as a complement to existing approaches to measure road vehicle emissions, in order to achieve a better understanding of the European issue of air pollution from road transport. The work presented in this report focuses on NO_X emissions from light-duty diesel vehicles, preferably passenger cars, corresponding to the Euro 4, 5 and 6 standards.

This work was part of the CONOX project[1], which was carried out during 2017 under a contract from the Federal Office for the Environment in Switzerland, FOEN (www.bafu.admin.ch).

[1] Study on comparing NO_X real driving emissions from Euro 5 and Euro 6 light-duty diesel vehicles as measured by remote sensing, PEMS and on chassis dynamometers

Table of contents

Summary

Remote sensing of vehicle exhaust emissions has been applied in Europe since the 1990'ies. Gaseous pollutant emission rates are measured as accurately as e.g. with PEMS instruments. The extra power of remote sensing comes from the big sample numbers and the fact that it is a non-intrusive technique. This CONOX project assembles the data from remote sensing measurement campaigns in Europe between 2011 and 2017. The unified database becomes a new research infrastructure allowing a finer than ever analysis of vehicles' emission performance with statistical representativeness.

Examples of the added value from remote sensing measurements include:

- Representative emission factors by manufacturer for all relevant Euro emission control stages;
- Cross-check of PEMS measurements with representative vehicle sample;
- Completion of PEMS measurements for brands, models and engine families not covered;
- Analysis of emission performance as a function of vehicle age;
- Analysis of emission performance as a function of ambient temperature;
- Cross-comparison of emission performance between countries: How valid is a single European emission factor?
- Analysis of share and contribution from high emitting vehicles.

The first three applications are illustrated in the following sections.

Introduction: What is remote sensing of vehicle exhaust emissions?

Remote sensing is a technique to measure pollutant emissions from vehicles while passing. Each emission record is matched with the engine load at the time. The vehicle's technical characteristics are taken from its registration data, identified from the number plate. Thus, with every vehicle being measured in passing the average emission behaviour is mapped over the range of engine loads encountered on the road. Accumulated tens of thousands of records provide a comprehensive picture of the fleet and allows disaggregation into broader vehicle categories. With eventually hundreds of thousands of records, as combined in the CONOX database, one can understand the emission behaviour of individual vehicle models under a wide range of driving and operating conditions as observed on the road. The following sections provide a short overview of outcomes from the CONOX project focussing in particular on the added value that vehicle emission remote sensing can provide.

The measurement principle

Remote sensing instruments determine incremental pollutant concentrations in the exhaust plume of vehicles passing, above the concentration in the ambient air at the time the vehicle is passing. These pollution increments are ratioed to the incremental CO_2 concentration in the plume, which is directly proportional to the amount of fuel consumed. Thus, each vehicle passing gets an emission rate assigned. In parallel its speed and acceleration are measured, which provide a measure for the vehicle's engine load. Combined, and with thousands of vehicles passing within hours, an ensemble of instantaneous emission rates over good parts of the engine map is created. The emission standard, fuel type, vehicle description, engine size and power, year of first registration, etc. are retrieved from the registration database. In this way the instantaneous emission rates are associated to vehicle makes, models, etc. with their respective technical characteristics.

CONOX: Unifying European measurements

Remote sensing measurements have been conducted in Europe since the early 1990's, notably in Sweden, Switzerland, and the UK, lately also in Spain and France (see Appendix for details and further references). Mostly this was done for research purposes. Each single campaign provided only for a limited scope and number of records. As a first step the data from remote sensing campaigns conducted since 2011 have been pooled together. This pool of currently 750,000 records has an unprecedented scope allowing for much more comprehensive analysis with high statistical significance. The project is named CONOX and is sponsored by the Swiss Federal Office for the Environment (FOEN) with in-kind contributions from the ICCT.

Within the CONOX project two methods were developed to convert between the RS measurement unit gram pollutant per kg fuel consumed and the cycle or trip based measurement unit gram pollutant per kilometer travelled. Both units are related by the fuel consumption at the respective engine load(s). This fuel consumption rate is either adjusted from measurements under average driving or modeled for the specific instantaneous engine load measured. The former method is rather straightforward but coarser while the latter is more adjusted yet requires much more data.

CONOX DB: A new research infrastructure

Remote sensing results from measurement campaigns conducted across Europe (Sweden, Switzerland, the UK, Spain and France) between 2011 and 2017 have been merged into a common database. The CONOX database now contains about 750,000 records with pollutant emissions, speed and acceleration, and vehicle technical data. The majority of records is from passenger cars and light commercial vehicles (Figure 1). More than 40% of records have been recorded in Spain, some 30% in Switzerland, almost 25% in the UK and the remaining 5% of stem from very recent measurements in Sweden. Key characteristics of individual campaigns are given in the Appendix. For further details, see CONOX Task 2 report[2].

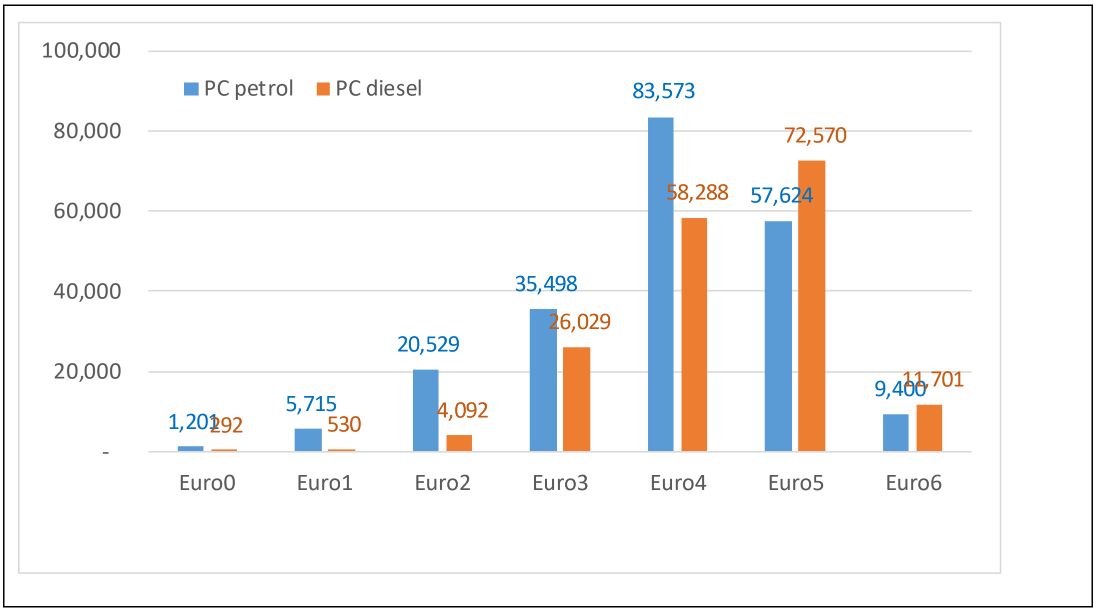

Figure 1: Number of RS records in the CONOX database for petrol and diesel cars and by Euro standard.

Added value of the enlarged data set

The true power of remote sensing rests in the large statistical scope. The analysis becomes much more comprehensive and strongly increases in accuracy with the number of (valid) records. Each single campaign contained normally 30,000 to 100,000 records. Combined into the CONOX database of 750,000 records, the statistical power increases by 5 to 20 times. More vehicles are covered, more driving conditions sampled, different instruments are included, a wider range of ambient (temperature) conditions, and a longer time series is established. We demonstrate the power of this new data pool with *the following analyses that all have not been feasible before by any other method with statistical certainty*:

- Emission rate per manufacturer;
- Emission rate for (top-selling) vehicle models;
- Dependence of the emission rate on the ambient temperature;

[2] 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. Real-driving emissions from diesel passenger cars measured by remote sensing and as compared with PEMS and chassis dynamometer measurements. IVL Report C XXXX.

- Development of emission performance with vehicle ageing.

Because of its importance and pertinence, the description is focused on the NOx emission rate from diesel passenger cars of Euro 5 emission standard. The same analysis can be done for Euro 6 cars. However, this emission standard has been introduced in several phases, meaning that it reflects actually several technical stages. Moreover, by 2016/7 the total number of records is more limited, less detailed analysis is feasible.

Results from pan-European measurements

Manufacturer hard- and software choices largely determine the resulting exhaust emissions, at least as concerns NOx emissions from diesel cars. Diesel cars of essentially all manufacturers have much higher NOx emissions in real driving than under certification test conditions. Official and 3rd party testing has covered a large number of popular brands but not all manufacturers. In addition, the multitude of individual vehicle models makes it difficult to recruit each single one for a thorough individual testing, let alone to have a statistically comprehensive sampling. Remote sensing measurements can help in with its much wider coverage:

- The whole fleet is covered by a RS measurement at once, no vehicle choice or exclusion involved;
- There is no sampling bias with RS but vehicles are measured in the state, age, driving and driver as they pass-by on the road; thus, results reflect the shares of manufactures and models in the actual fleet;
- There are many repeat measurements with RS, and the uncertainty in the results is explicitly documented.

Remote sensing has been developed since the late 1980'ies and measures on-road emission rates with the same accuracy as e.g. standard PEMS instruments. For instance, both measurement techniques very clearly show increasing NOx emission rates with increasing engine load (Figure 2).

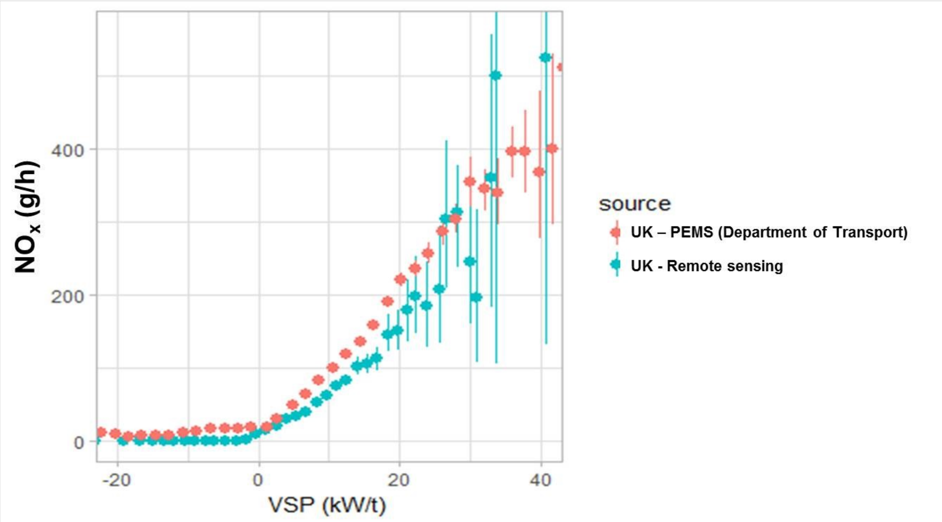

Figure 2: NOx emission rate [g/h] as a function of engine load [VSP in kW/t] for Euro 6 diesel cars as recorded by remote sensing and by PEMS measurements. Data sources: RSD: CONOX; PEMS: Official on-road testing by UK DfT. David Carslaw for this project.

When comparing RSD measurements with e.g. PEMS trips, it is important to account for differences in engine load which can explain a good part of a potential difference. Other reasons lie in differences in the ambient conditions, but also in sampling bias, i.e. differences between individual PEMS tested vehicles and the mix of models actually driven on the road. Notwithstanding aggregate results between RSD and PEMS match as good as can possibly be expected (Figure 3).

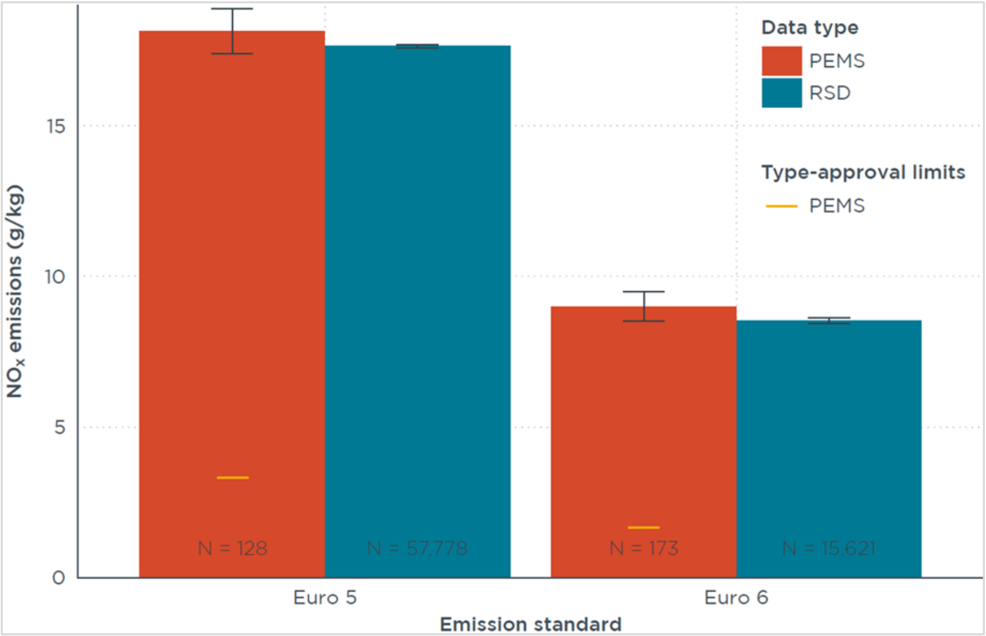

Figure 3: **Comparison of the average NOx emission rate for diesel Euro 5 and Euro 6 cars as measured by RSD and by PEMS. Data sources: RSD: CONOX; PEMS (official on-road testing from FR, DE, NL, UK only)[3]. Y. Bernard & U. Tietge for this project.**

Exhaust emissions by manufacturer

RSD provides an ad-hoc overview of the emission rate of the fleet driven. This can, for instance be further broken down by vehicle manufacturer group and brand (Figure 4): The average NOx emission rate for diesel cars of the ”better in class” brands is two times lower than the ”worst in class”. Nonetheless we can ascertain that all brands exceed the NOx certification limit for Euro 5 cars by far. Grouped by manufacturer a distinct pattern becomes apparent: Cars from the Renault/Nissan and the Fiat/Chrysler group score worst, the BMW group scores best, and Volkswagen and PSA group cars are in the broad medium range.

In between are numerous brands that have only been rarely tested, if at all, in the official investigations. Thus, remote sensing provides a more complete picture of the actual on-road emission performance of the fleet as driven in urban areas.

Looking ahead to the recently mandatory Euro 6 standard, we observe strongly increased differences between the brands. Most have reduced their emission rate significantly but a few

[3] C. Baldino et al., “Road Tested: Comparative Overview of Real-World versus Type-Approval NOx and CO2 Emissions from Diesel Cars in Europe,” White Paper (Berlin, Germany: The International Council on Clean Transportation (ICCT), September 2017), http://www.theicct.org/sites/default/files/publications/ICCT_RoadTested_201709.pdf.

brands have even higher than for their Euro 5 models (Dacia, Fiat, Renault). We can confirm with the mass sampling that the Euro 6 models of the Volkswagen group now belong to the diesel cars with lower than average NO emissions.

Such kind of assessments become possible with a representative on-road sampling of the whole fleet as driven, provided by remote sensing campaigns.

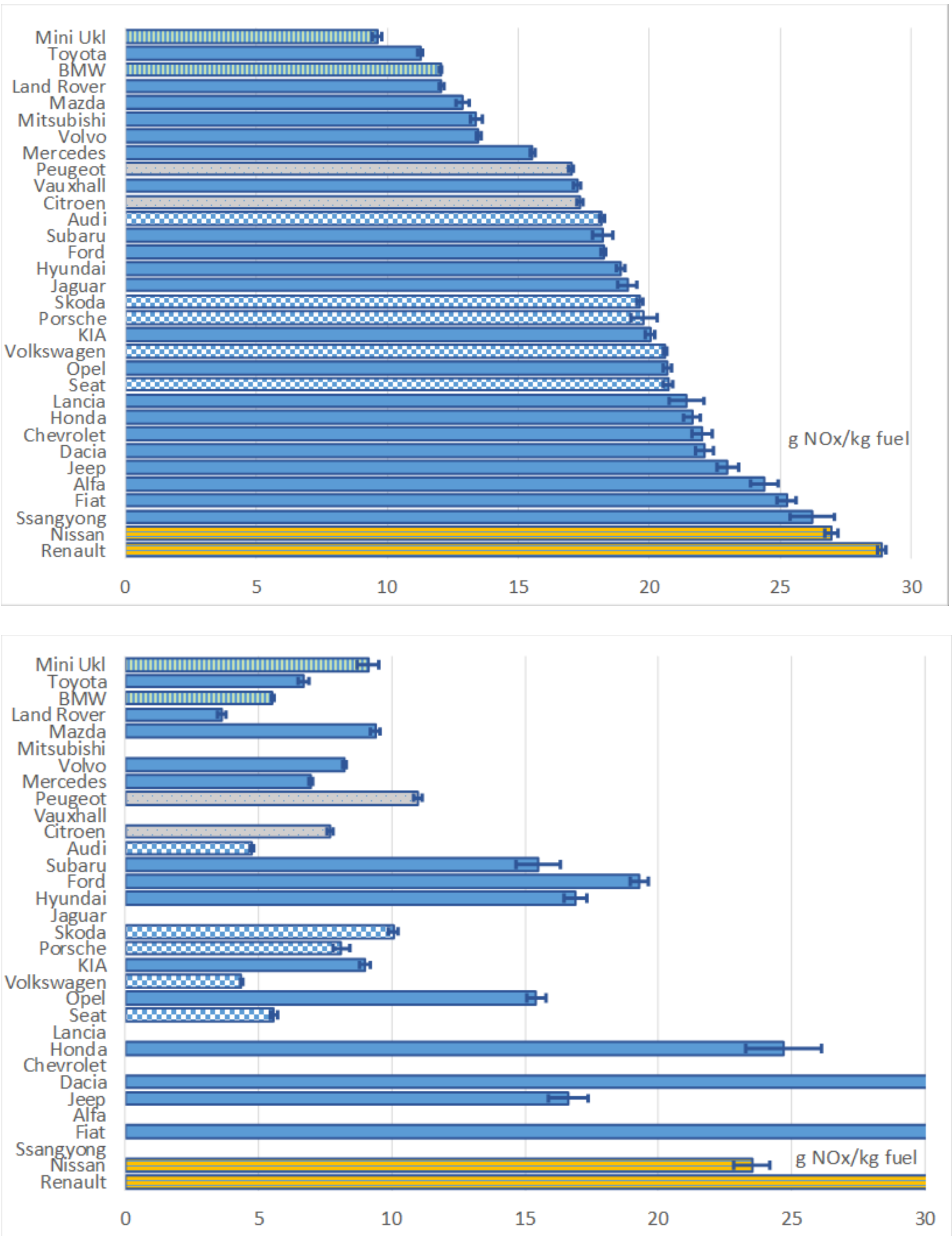

Figure 4: Average NOx emission rate from diesel cars by brand (Euro 5 top; Euro 6 bottom), as measured by remote sensing in Sweden, Switzerland, the UK and Spain between 2011 and 2016. Colour coded are brands belonging to the same manufacturer. Ordered by increasing emission rate for Euro 5. Source: CONOX database; filtered for VSP [0, 30] kW/t; results only displayed when more than 30 records per brand available.

Remote sensing measurements complementing PEMS data

With large sample sizes as in the CONOX database it is possible to go one step further: Analyse the emission rate per vehicle model with statistical representativeness. Here, we choose to compare remote sensing results with the emission rates from the numerous official investigations in the wake of dieselgate. The comparison is focused on the top ten best-selling models in Sweden, Switzerland, the UK and Spain during the period 2011 to 2015, cumulated.

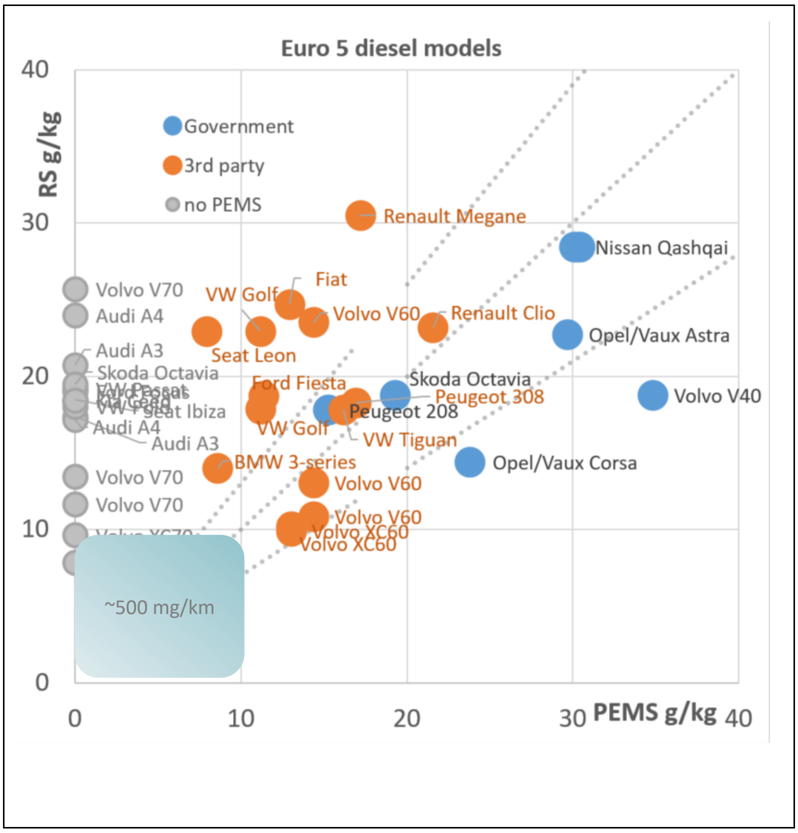

Figure 5: **NOx emission rates from Euro 5 diesel cars for the 10 ten best-selling models in CH, SE, UK, ES as measured by remote sensing and in PEMS investigations (official: blue marker; 3rd party testing: orange marker; no PEMS test: gray marker). Models with the same designation differ in engine displacement. The equivalent range of 500 mg NOx per km is indicated in the bottom-left corner. Source RS: CONOX database; VSP [0, 30] kW/t; at least 30 records each. Source PEMS data: ICCT's db of PEMS records; only non-NEDC tests, only if NOx and CO2 were measured at same time. The dotted lines indicate the identity line and ±30% uncertainty.**

The comparison between RS and PEMS measurements for e.g. the top 10 best-selling Euro 5 diesel cars shows (Figure 5):

- Agreement on the NOx emission rate within a standard uncertainty of ±30%;
- Governmental tests (blue markers) only cover a small part of the top-selling models;
- 3rd party testing (orange markers) is important for a more comprehensive picture on the emission performance of vehicle models (grey markers for which PEMS measurements are not available);

- Remote sensing covers the top 10 best-selling models in different markets, while even the extensive PEMS measurements combined leave out about one third of models.
- No models come close to the certification limit value in real driving, but some manufacturers seem to perform systematically better and worse than others (compare with Figure 4 for the manufacturer group's average).
- The model designation is not a relevant discriminator for the emission performance (not labelled in the figure): For instance, Volvo's V60 and V70 models come with three engine sizes (1.6l, 2.0l, 2.4l). The Volvo models with the same engine displacement have a similar NOx emission rate, while the same model but different engine displacement are markedly different.

It is not our purpose here to discuss the coincidence or apparent discrepancies of individual models. Suffice to point out that

- more than one specific car per model variant was hardly tested in the official PEMS inquiries. This makes results very contingent on this vehicle.
- PEMS measurements exhibit themselves a larger spread across trips; hence the result cannot be considered as a point measurement but rather as indicative of the range under real driving conditions.
- Differences between PEMS and RS testing conditions makes it reasonable to assume that resulting emission rates are not identical.

It's important however, that most of these differences are random. They average out with a sufficiently large sample size: The averages between the two samples match almost perfectly. In conclusion, both RS and PEMS provide relevant emission rates, and when either techniques shows an elevated emission rate then there is need for action and follow-up.

This comparison here focuses on the top selling models in the four remote sensing countries, and it focuses on the more recent (Euro 5 and early Euro 6) diesel cars for which there have been comprehensive PEMS measurements. However, remote sensing data are available for the whole fleet of light-duty vehicles including older diesel cars certified to Euro 2, 3 and 4 emission standards as well as the whole fleet of gasoline cars as well as a comprehensive number of vans and light commercial vehicles.

In conclusion, remote sensing covers in a campaign with easily 100,000 records a wide range of vehicles as driven on the road. This provides a quick and reliable overview of the actual fleet emissions. No other method can compete with the low sampling costs of the order of 1 Euro per valid record. As a passive sampling this can complement measurement techniques like PEMS and chassis dynamometer tests that allow experimenting with individual vehicles and that can select dedicated vehicles independent of their actual market penetration (though more often than not this is bound by budget and vehicle availability)

Age and temperature dependence of emission performance

The large and detailed set of combined RS data provides an unprecedented statistical power for further analysis. Within the scope of this project we've analysed notably

- The dependence of the emission rate on the ambient temperature from 5 ^{o}C to 30 ^{o}C;
- The long-term emission performance of vehicles as a function of vehicle age.

First results are summarized in the CONOX Task 2 report; more analysis beyond the scope of the current assignment is warranted and promising.

The place of remote sensing in vehicle emission measurements

In many respects, remote sensing is complementary to both chassis dynamometer and PEMS testing: Vehicles are measured remotely as driven in everyday traffic; the measurement equipment does not physically interact with the vehicle undergoing testing; the vehicle's operator is typically unaware of the emissions test; and vehicle operating conditions and ambient conditions are not predetermined. While each single measurement is no more but also no less than an instantaneous record, the ensemble of hundreds of thousands or eventually millions of records provides a comprehensive, reliable and differentiated picture of the emission performance of the whole fleet.

Remote sensing results can be used to inform additional, more detailed tests using, for example PEMS, to subject the vehicle to specific test conditions. In this way, remote sensing can efficiently screen the fleet and inform the selection of vehicles for the costlier single vehicle and more detailed PEMS tests. The accuracy and representativeness of remote sensing results are essentially determined by the choice of measurement sites, by the variation of the vehicles passing, and the total amount of valid emission measurements. The accuracy can be easily increased by larger sample sizes[4], the representativeness by more measurement sites. Both are under the control of the testing authority.

Vehicle emission remote sensing can determine the emission rates of the whole fleet, of specific vehicle types, or vehicle classes by emission standard, age, driving condition, temperature, etc., in a relatively quick and cost-effective manner. As such, there are several clear areas in which remote sensing provides added-value to existing vehicle emissions test methods to support better real-world control of emissions from motor vehicles. As demonstrated, even hundreds of chassis and PEMS measurements combined do not reach a sufficient coverage of even the most important manufacturers and brands, let alone models and their variants, in European countries. Therefore, the mass sampling of real-world emissions as possible by remote sensing is a unique opportunity to stay up-to-date with the emission performance of the fleet as driven.

[4] For instance, if the sample size is doubled, the standard error of the average measured emission will be reduced by 30%, if the sample size is increased tenfold, the standard error of the average measured emission will be reduced by a factor of more than 3.

Next steps and further issues

The creation of the CONOX database as a new research tool is the major achievement of this project. We've illustrated above some of the new analytical possibilities that thus became available. This advances our understanding but invites also for more profound and comprehensive analysis. Therefore, we recommend the following next steps:

- Maintain the database: Develop routines for data checking and integration;
- Augment database with data from on-going campaigns, possibly also with older campaigns
- Continue analysing, e.g. how emission rates compare between countries, how emissions vary within an engine family, how the manufacturer mix influences the fleet average emissions in a country;
- Analyse other vehicle categories, such as light and heavy commercial vehicles, buses and motorcycles.
- Disseminate and integrate with measurement data from chassis dynamometer and PEMS investigations (i.e. notably with the ERMES database).
- Validate and refine the proposed conversion methods;
- Analyse emission rates for other pollutants than NOx;
- Determine possible contribution from individual high emitters.

As any other technique there are a few limitations with the application of remote sensing:

- It's an observation of vehicles passing but there are only a very limited options to actively experiment with the vehicle (some traffic guidance with speed and acceleration bounds might however be possible).
- No active recruiting, this means no sampling bias but it also means, that e.g. rare vehicles, e.g. latest vehicle models, can only be measured to the extent they are present in the fleet.

Output from the CONOX project

The interest in on-road remote sensing has been high and there have already been noticeable output from the CONOX project, apart from the three reports produced within the project, as listed below:

- Quick update of HBEFA 3.3 using preliminary temperature analysis from CONOX. Ake Sjodin, Gian-Marco Alt.
- Presentations at the European Parliament on the potential role of RS in market surveillance (28 Sept 2017) – Ake Sjodin, Yoann Bernard.
- Presentations at the ERMES meeting 14 Nov 2017 – Harald Jenk & James Tate; Jens Borken-Kleefeld.
- Presentations at the TAP Conference 15.-16. Nov. 2017 – David Carslaw, Ake Sjodin, Jens Borken-Kleefeld.
- Use of CONOX data and unit conversion in ICCT's TRUE project with the cities of London and Paris.

Appendix

European remote sensing campaigns – overview

The list gives an overview of remote sensing campaigns that have been conducted in Europe. This shows both, the long standing use of this measurement technique but also the relatively modest scale of many of the earlier campaigns. This makes pooling and sharing of data all the more important to attain a certain statistical power for the data analysis.

The current CONOX database contains only data from RS campaigns conducted between 2011 to (early) 2017. Those are highlighted in the following. It is important to continue feeding current campaigns into the database. In addition, for certain types of analysis, it will also be worthwhile to include older data in the database.

Sweden

Sweden has pioneered Europe's first application of on-road vehicle emission remote sensing in the early 1990s. The first study carried out in 1991 aimed at evaluating the real-world emission performance of three-way catalyst cars (relative to the emission performance of the older gasoline passenger car fleet, lacking closed-loop emission control), a few years after they were first introduced in the Swedish market (Sjödin, 1994a). Later on – in the mid 1990s – remote sensing was evaluated as a means to support roadside inspections involving an idle emission test (Sjödin, 1994b) and for identifying and repairing high-emitting catalyst cars (Sjödin et al., 1997).

Since then, a number of various remote sensing emission measurement campaigns have been conducted more or less on an annual or biennial basis, most recently in 2016. Each campaign has had a different, dedicated objective:

- Validate, and where necessary revise, emission factors of light duty vehicles, both gasoline and diesel powered, for the Swedish situation.
- Driver awareness raising and voluntary emission reductions by presenting emission results in real-time from remote sensing measurements on a roadside display.
- Determine on-road emissions from heavy-duty buses and trucks, including CNG powered urban buses.
- Determine NO and NO2 emissions from light duty diesel vehicles in real-world driving.
- Monitor emission level from latest technologies, notably Euro 6 diesel cars.

Location	Years	# records	Site characteristics	Ref.
Stockholm / SE	1991	10,000	Freeway interchange ramp, +3% grade, speed limit 40 km/h. First attempt in Europe to evaluate the real-world emission performance of three-way catalyst cars	Sjödin, 1994a
Gothenburg and Linköping / SE	1993	10,000	Four different sites: One freeway interchange ramp (+3%, speed limit 70 km/h), two city streets (both flat and speed limit 50 km/h) and one rural road (flat, speed limit 70 km/h). First measurements involving speed & acceleration	Sjödin & Lenner, 1995
Stockholm / SE	1994	9,000	Several sites, typically city streets with slight to moderate positive grade, speed limit 50 km/h. Supporting idle emission (I/M) testing at roadside.	Sjödin, 1994b
Stockholm / SE	1995-1998	50,000	Commuting route, slightly uphill. Identification and repair & maintenance of high-emitters	Sjödin et al., 1996; Sjödin et al., 1997ab
Gothenburg / SE	2001-2007	≈1,000,000	Several sites in the city of Gothenburg and suburban areas, speed limit typically 50 km/h, from flat to moderate uphill grades. Supporting driver and public awareness raising of motor vehicle emissions (”SmartSign”)	Sjödin, 2005
Gothenburg / SE	2014 & 2016	34,000	Two freeway interchange ramps, +3% grade, speed limit 40 km/h and 70 km/h, respectively. Long-term studies of real-world road vehicle emission trends and evaluation of road vehicle emission models	Sjödin & Andréasson, 2000; Ekström et al., 2004; Sjödin et al., 2006; Sjödin & Jerksjö, 2008

Sjödin, Å. (1994a) On-Road Emission Performance of Late-Model TWC-Cars as Measured by Remote Sensing, J. Air & Waste Managem. Assoc. 44, 397-404.

Sjödin, Å. (1994b) Potential of a Remote Sensing Technique in Roadside Inspections - Experiences from a Pilot Study in Sweden. In: Proc. 27th International Symposium on Advanced Transportation Applications (ISATA), Aachen, Germany, October 31- November 4, 1994.

Sjödin, Å., Lenner, M. (1995) On-Road Measurements of Single Vehicle Pollutant Emissions, Speed and Acceleration for Large Fleets of Vehicles in Different Traffic Environments. Science of the Total Environment 169, 157-166.

Sjödin, Å., Andréasson, K., Wallin, M., Lenner, M., Wilhemsson, H. (1997a) Identification of High-Emitting Catalyst Cars on the Road by Means of Remote Sensing. Int. J. Vehicle Design 18, 326-339.

Sjödin, Å., Andréasson, K., Wallin, M. (1997b) Multi-Year Repeat Remote Sensing Measurements of On-Road Emissions from Cars Subject to an Annual Centralised I/M-Program Involving an Idle Emission Test. In: Proc. 7th CRC On-Road Vehicle Emissions Workshop, San Diego, 9-11 April, 1997.

Sjödin, Å., Andreasson, K. (2000) Multi-Year Remote Sensing Measurements of Gasoline Light-Duty Vehicle Emissions on a Freeway Ramp. Atm. Environ. 34, 4657-4665.

Ekström, M., Sjödin, Å., Andreasson, K. (2004) Evaluation of the COPERT III emission model with on-road optical remote sensing measurements. Atm. Environ. 38, 6631-6641.

Ekström, M., Sjödin, Å., Andréasson, K. (2005) On-road optical remote sensing measurements of in-use bus emissions. 14th International Symposium Transport & Air Pollution, Graz, Austria, June 1-3, 2005.

Hallquist, Å. M., Jerksjö, M., Fallgren, J., Westerlund, J., Sjödin, Å. (2012) Particle and gaseous emissions from individual diesel and CNG buses. Atmos. Chem. Phys. Discuss. 12, 27737-27773.

Jerksjö, M. (2016) On-road emission measurements in Sweden 2007-2015. 21st International Symposium Transport & Air Pollution, Lyon, 24-26 May, 2016, 240-254.

Switzerland

The longest time series of remote sensing measurements in Europe if not worldwide has been recorded at the outskirts of Zurich/Switzerland. The Office of Waste, Water, Energy and Air of Zurich Kanton have monitored their light duty fleet in every year since 2000, always at the same location, the same season, with minimal change in instrumentation and operating personnel[5,6]. These measurements have served:

- to characterize the emission rate of the on-road fleet of light duty vehicles in the Kanton, both passenger cars and light commercial vehicles, gasoline and diesel powered alike. The penetration of diesel cars is clearly captured as well as their high on-road NO/NOx emissions. The successive introduction of new vehicle exhaust emission standards into the fleet is monitored, showing a steady decrease in the emission rate of gasoline cars, whereas the NOx emission rate of diesel cars has even increased for over a decade[7].
- The data set is rich enough to be differentiated by model year and emission standard; the long time series has allowed for deriving deterioration rates for gasoline[8] and diesel cars[9].
- The measurement site stands out from others elsewhere because of an uphill gradient of 9%. This allows for measuring emissions under higher power demand from the vehicles' engines under otherwise urban driving conditions.
- Researchers have used this rich data set to cross-check on-road emission rates for passenger cars and light commercial vehicles as used in HBEFA[10], COPERT, and VERSIT[11],

[5] M. Goetsch, "Bericht Und Auswertung RSD Messungen 2012" (Zurich/CH: Amt für Abfall, Wasser, Energie und Luft, Lufthygiene, Baudirektion Kanton Zurich, March 20, 2013), http://www.ji.zh.ch/content/dam/baudirektion/awel/luft_asbest_elektrosmog/verkehr/rsd/dokumente/RSD_Bericht_2012.pdf.

[6] M. Goetsch et al., "RSD Messungen 2016: Auswertung Und Bericht" (Zurich/CH: Amt für Abfall, Wasser, Energie und Luft, Abteilung Luft, Baudirektion Kanton Zurich, April 21, 2017), http://www.awel.zh.ch/content/dam/baudirektion/awel/luft_asbest_elektrosmog/verkehr/rsd/dokumente/RSD_Bericht_2016.pdf.

[7] 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.

[8] 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.

[9] Y. Chen and J. Borken-Kleefeld, "NOx Emissions from Diesel Passenger Cars Worsen with Age," *Environmental Science & Technology* 50, no. 7 (March 9, 2016): 3327–3332, https://doi.org/10.1021/acs.est.5b04704.

to compare emissions by vehicle brand and model, searching for high-emitters[12], among others.

Location	Years	# records	Site characteristics	Ref.
Zurich/Switzer-land	2000 to 2010 annually during 8-12 weeks.	~275'000	Extra-urban, 9% uphill gradient	AWEL various years; EMPA 2003
Zurich/Switzer-land	2011 to 2017 annually during 8-12 weeks.	~275'000	Extra-urban, 9% uphill gradient	Latest: AWEL 2017; EMPA 2016

EMPA 2003: Abgasvergleichsmessung Remote Sensing Detector (RSD) - Rollenprüfstand, EMPA Report 429353.

AWEL 2011: Amt für Abfall, Wasser, Energie und Luft der Baudirektion des Kantons Zürich, Bericht und Auswertung RSD Messungen 2011.

AWEL 2017: Amt für Abfall, Wasser, Energie und Luft der Baudirektion des Kantons Zürich, Bericht und Auswertung RSD Messungen 2016.

EMPA 2016: Pilotprojekt Vergleichsmessungen Remote Sensing - PEMS - Rollenprüfstand im Auftrag des Bundesamts für Umwelt BAFU, EMPA-Bericht Nr. 5214010202.01.

United Kingdom

There have been many measurement campaigns across various cities in the UK in the past years: Vehicle emissions in central and sub-urban London have been intensely measured in repeated campaigns, with particular emphasis to determine NO and primary NO2 emissions from diesel cars, from taxis and buses[13]. Efforts have been made to analyse the impact of specific after-treatment technology and/or vehicle manufacturers on the resulting emissions, notably for taxis

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[10] Jörg Kühlwein et al., "Update of Emission Factors for EURO 5 and EURO 6 Passenger Cars for the HBEFA Version 3.2," Final Report (Graz, Austria: IVK, TU Graz, October 16, 2013); M. Keller et al., "HBEFA Version 3.3 - Background Documentation" (Bern/CH, April 25, 2017).

[11] P. S. van Zyl et al., "In-Use Compliance and Deterioration of Vehicle Emissions" (Delft, NL: TNO, July 8, 2015), http://www.emissieregistratie.nl/erpubliek/documenten/Lucht%20(Air)/Verkeer%20en%20Vervoer%20(Transport)/Wegverkeer/TNO%20(2015)%20In-use%20compliance%20and%20deterioration%20of%20vehicle%20emissions.pdf.

[12] J. Borken-Kleefeld, "Remote Sensing for Identifying High Emitters and Validating Emission Models" (19th International Transport and Air Pollution Conference 2012, Thessaloniki, Greece, November 26, 2012).

[13] David C. Carslaw et al., "Recent Evidence Concerning Higher NOx Emissions from Passenger Cars and Light Duty Vehicles," *Atmospheric Environment* 45, no. 39 (December 2011): 7053–63, https://doi.org/10.1016/j.atmosenv.2011.09.063; D. Carslaw and G.A. Rhys-Tyler, "Remote Sensing of NO2 Exhaust Emissions from Road Vehicles," A report to the City of London Corporation and London Borough of Ealing (King's College London & Newcastle University/UK, May 2013), file:///C:/HOME/IIASA/HighEmitters/Lit/DefraRemoteSensingReport_2013.pdf; D. Carslaw and M. Priestman, "Analysis of the 2013 Vehicle Emission Remote Sensing Campaigns Data" (London, UK: King's College London, February 2015), https://uk-air.defra.gov.uk/assets/documents/reports/cat15/1511251131_Analysis_of_the_2013_vehicle_emission_remote_sensing_campaigns_data.pdf; David C. Carslaw et al., "Have Vehicle Emissions of Primary NO2 Peaked?," *Faraday Discuss.* 189 (2016): 439–54, https://doi.org/10.1039/C5FD00162E; David C. Carslaw and Glyn Rhys-Tyler, "New Insights from Comprehensive On-Road Measurements of NOx, NO2 and NH3 from Vehicle Emission Remote Sensing in London, UK," *Atmospheric Environment* 81 (December 2013): 339–47, https://doi.org/10.1016/j.atmosenv.2013.09.026.

and buses. Results have been published widely and serve as input to ongoing efforts to reduce London's PM and NO2 air quality problems.

Measurement campaigns have also been conducted in other cities across the UK, mostly with the aim to characterize the emission rate of the local fleet: Light duty vehicles as well as some heavy-duty vehicle have been measured in Aberdeen, Leeds, Oxford, Cambridge, York, Sowerby, Halifax, a.o. since 2009 (mostly by James Tate from ITS Leeds[14]). Again, these measurements at various places gave rise to a number of research articles, for instance:

- characterizing the higher power regimes that are disproportionately intensive in emissions, analyzing temporal trends over various Euro classes, differentiated emission rates by vehicle manufacturer/brand.
- The use of vehicle remote sensing instruments has been considered as a tool for monitoring Low Emission Zones, by filtering out vehicles with emissions above the allowed threshold.
- The emission rates measured with remote sensing used to validate emission models, in particular the UK national emission inventory model.

Lastly, the instantaneous emission rates are used as input for an instantaneous emission model with the purpose to calculate the very localized emissions e.g. at traffic intersections and individual streets.

[14] Carslaw et al., "Recent Evidence Concerning Higher NOx Emissions from Passenger Cars and Light Duty Vehicles"; 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.

Location	Years	# records	Site characteristics	Ref.
UK, various locations	2007 to 2010	84’000	7 urban sites	Carslaw et al. AE 45, 2011
London / UK	2008	55’000	13 sites dense urban	Rhys-Tyler & Bell 2012
London / UK	2012	76’000	3 sites dense urban, 1 site on-ramp to highway. Detailed analysis of NO2 emissions, on taxis and urban buses.	Carslaw & Rhys-Tyler, 2013
York / UK	2012	8’000	5 urban/extra-urban sites across town	Tate 2008
Bradford / UK	2012	12’000	2 urban/extra-urban sites across town	Tate 2013
Leeds / UK	2012	8’000	2 urban/extra-urban sites across town	Tate 2013
Canterbury / UK	2012	18’000	5 urban/extra-urban sites across town	Tate 2013
Cambridge / UK	2013	15’000	5 urban/extra-urban sites across town	Tate 2013
Sheffield / UK	2013	28’000	5 urban/extra-urban sites across town	Tate 2013
Leeds / UK	2013	700	Off-carriageway (public highway) remote sensing instrument inter-comparison study (RSD4600 & FEAT)	Rushton, Tate, Carslaw & Shepherd 2017
Aberdeen / UK	2015	24’000	5 urban/extra-urban sites across town	Tate 2016

Tate, J. 2013: Vehicle Emission Measurement and Analysis - Cambridge City Council. Draft Project Report. University of Leeds, Institute for Transport Studies. 28 Nov 2013.

Tate, J. 2013: Vehicle Emission Measurement and Analysis – Sheffield City Council. Final Project Report. University of Leeds, Institute for Transport Studies. 3 Dec 2013.

Tate, J. 2016: Vehicle Emission Measurement and Analysis - Aberdeen City Council. Final Project Report. University of Leeds, Institute for Transport Studies. 7 April 2016.

Rushton, C., Tate, J., Shepherd, S., Carslaw, C. 2017. Inter-Instrument Comparison of Remote Sensing Devices and a New Method For Calculating On Road NOX Emissions and Validation of Vehicle Specific Power. Journal of the Air and Waste Management Association.

Spain

In Spain, remote sensing has been used to characterize on-road vehicle emissions in the major cities for about a decade. The data has been used for the design of mobility policies and the identification of high emitters in the fleet. For example:

- Identification of high levels of NOx emissions in municipal buses in Valencia using biodiesel as fuel.
- Identification of large HC emitters in trucks of some fleets due to the use of altered and cheaper fuels.

In 2011, inter-comparison studies with PEMS began in the context of some research projects with scientific partners such as CIEMAT or Carlos III University. A Spanish technology company has been accredited by ISO 17025 for its remote sensing measurements in 2013[15]. The Spanish Ministry of Environment proposed a draft Royal Decree[16] for the identification of High Emitter vehicles based on vehicle remote sensing. The remote sensing technology has been further validated since and high emitter thresholds have been investigated in the CORETRA project (2014/15). Current work is focusing on automatization of the gas calibration of the instrument and on supporting a mandatory legislation for high emitter detection in Spain.

In 2017 a larger vehicle measurement campaign in conducted in Spain to better characterize on-road emissions and vehicles.

The Spanish laboratory, OPUS Remote Sensing Europe, formerly RSLAB, has also carried out in the last two years characterization projects in France (Lille), in Iran (Teheran) and Ghana.

Location	Years	# records	Site characteristics	Ref.
Valencia / ES	2008	16’750	6 urban sites across town	Technet & AJ Valencia 2008
Madrid / ES	2008	24’800	6 urban sites across town	Technet & AJ Madrid 2008
Sevilla / ES	2009	26’200	7 urban sites across town	Technet & AJ Sevilla 2009
Metropolitan City / ES	2010	50’000	14 urban sites, 1 site focusing taxis 1 site in port focusing on trucks	Technet & AJ NN 2010
Granollers / ES	2011	10’000	2 urban sites	Technet 2012

[1515] https://rslab-es.jimdo.com/iso-17025/
[16] http://www.mapama.gob.es/es/calidad-y-evaluacion-ambiental/participacion-publica/PP_2013_Proyecto_RD_emisiones_vehiculos.aspx#

Madrid Region / ES	2014-2015	200'000	28 urban and extra-urban sites in the Capital Region, including on-highway ramps	Pujadas et al. SciTotEnv 2017
Lille / FR	2016	20´000	5 urban sites	RSLAB
Metropolitan City / ES	2017	Around 150.000	15 urban sites and 10 regional sites	RSLAB

Technet & Ayuntamento de Madrid 2008: Informe de caracterización del tráfico en materia de emisiones con el sistema de medición a distancia de contaminantes, "RSD", en la ciudad de Madrid. Madrid 15 Apr 2008.

Technet & Ajuntament de Valencia 2008: Informe de caracterización del tráfico en materia de emisiones con el sistema de medición a distancia de contaminantes, "RSD", en la ciudad de Valencia. Madrid/Valencia 15 Sept 2008.

Technet & Junta de Andalucia 2009: Informe de caracterización del tráfico en materia de emisiones con el sistema de medición a distancia de contaminantes, "RSD", en la ciudad de Sevilla. Madrid/Sevilla, 31 Mar 2009.

Technet & Ajuntament de NN 2010. Estudio de caracterización del tráfico rodado en materia de emisiones en la ciudad de NN. NN/Madrid, April 2010

Technet & Ayuntamento Granollers 2012: CARACTERIZACIÓN DE LAS EMISIONES DEL TRÁFICO EN GRANOLLERS. Madrid Mar 2012. http://www.granollers.cat/sites/default/files/antigues_d6/pagina/2012/06/20120531_Resumen%20Ejecutivo_FG.pdf

Pujadas, M., A. Domínguez-Sáez, and J. De la Fuente. 2017. "Real-Driving Emissions of Circulating Spanish Car Fleet in 2015 Using RSD Technology." Science of The Total Environment 576 (January): 193–209.

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