WHITE PAPER FEBRUARY 2018

REMOTE SENSING OF MOTOR VEHICLE EXHAUST EMISSIONS

Jens Borken-Kleefeld and Tim Dallmann

THE INTERNATIONAL COUNCIL
ON CLEAN TRANSPORTATION

www.theicct.org

communications@theicct.org

BEIJING | BERLIN | BRUSSELS | SAN FRANCISCO | WASHINGTON

ACKNOWLEDGMENTS

Funding for this work was generously provided by the European Climate Foundation and the FIA Foundation. The authors would like to thank Yoann Bernard, Fanta Kamakaté, Ray Minjares, Peter Mock, Rachel Muncrief, and members of the CONOX group for their helpful discussions and review of this report. Their review does not imply an endorsement, and any errors are the authors' own.

International Council on Clean Transportation
1225 I Street NW Suite 900
Washington, DC 20005 USA

communications@theicct.org | www.theicct.org | @TheICCT

TABLE OF CONTENTS

EXECUTIVE SUMMARY

European motor vehicle emission control legislation has not been effective in controlling emissions of all regulated air pollutants from light-duty diesel vehicles. Deficiencies in the current regulatory approach have been made clear in recent years. More and more diesel car manufacturers have been found to have deliberately circumvented the spirit of emission control legislation by optimizing systems to the very specific conditions of laboratory emission test programs, as opposed to designing effective control of emissions during real-world driving. Consequently, many diesel cars in Europe emit nitrogen oxides (NO_X) at rates significantly higher than nominal regulatory limits when driven in real-world conditions. These excess emissions have exacerbated urban air quality problems in European cities and have been linked to thousands of premature deaths each year.

Actions are now being taken to strengthen the European regulatory program for light-duty vehicles, including a transition to a more representative laboratory emissions testing procedure, the introduction of real-driving emissions (RDE) test requirements using portable emissions measurement systems (PEMS), and revisions to the existing type-approval and market surveillance framework. While these are positive steps, it remains to be seen whether provisions will not be circumvented again, in particular as vehicle systems can still detect when a car is being run through the new testing procedures. Therefore, we argue, there is a need to complement with alternative emissions test methods in order to monitor and ensure the effectiveness of the European motor vehicle emissions control program. This paper considers one such method, vehicle emissions remote sensing, which has been used for more than 25 years to measure emissions from passing motor vehicles in real-world driving.

The purpose of the paper is threefold:

1. To review technical details of the vehicle remote sensing test method;
2. To describe the multiple types of emissions analyses that can be conducted with remote sensing data, and
3. To explore areas where remote sensing can supplement emission test methods currently used in the EU light-duty vehicle regulatory program.

Vehicle emission remote sensing differs from all other regulatory emissions test methods in that the testing equipment does not physically interact with the vehicle undergoing testing. Rather, a light source and detector, placed either at the side of or above a roadway, are used to measure exhaust emissions remotely via spectroscopy as vehicles pass by the measurement location. In this way, remote sensing measurements yield snapshots of emission rates from thousands of individual vehicles as they are driven on actual roadways by their owners. Speed and acceleration are measured at the same time as the emissions measurement, providing information about the engine load. Finally, a camera captures an image of the vehicle’s number plate, allowing for the retrieval of essential vehicle information—make, model, model year, certified emission standard, fuel type, rated power—from vehicle registration databases. Thus, the ensemble of remote sensing measurements provides air pollutant emission rates for the fleet across a wide range of driving conditions. These data can be sorted by vehicle category (e.g. by fuel and Euro standard), brand, possibly vehicle model, and eventually down to the level of individual vehicles, as much as the overall sample size allows.

Remote sensing offers several advantages relative to PEMS or chassis dynamometer testing:

- A large number of vehicles can be sampled in a short period of time. In a single day, a remote sensing setup can be used to measure emissions from thousands of vehicles; PEMS and dynamometer methods typically can test less than five vehicles in a similar time period.
- Remote sensing measurements are reflective of real-world conditions in that they are not subject to a predefined set of driving conditions, and measurements may be conducted under a wide range of ambient environmental conditions.
- Remote sensing is harder to detect (or anticipate) and hence to game. The test vehicle is separated entirely from the emissions test equipment, making it extremely difficult for vehicle engineers to design systems to detect remote sensing emissions testing.
- Recruitment bias is minimized, as remote sensing allows for greater fleet coverage and vehicles undergoing emissions testing are not preselected.

A single instantaneous emission rate, i.e., a single remote sensing record, has the same limitations as a second's record from a PEMS or chassis dynamometer test. However, the ensemble of millions of records becomes comparable to many, many chassis or PEMS tests. Remote sensing can thus provide a comprehensive, reliable, and differentiated picture of the emission performance of the whole fleet, its constituent vehicle categories, the different brands and model families, and eventually, with sufficient data, individual vehicles.

There are many ways remote sensing data can be aggregated and analyzed to provide information on the emissions performance of in-use motor vehicles. Remote sensing data can determine emission rates for whole fleets, for specific vehicle types, for vehicle classes by emission standard, and even, given sufficient data are available, for distinct vehicle makes and models. Data can be used to evaluate the effect of parameters, such as engine load and ambient temperature, on vehicle emissions. Finally, remote sensing can be used to evaluate the durability of emissions control systems and to track the emissions performance of vehicle fleets over time. In all cases, the accuracy and representativeness of remote sensing results are essentially determined by the choice of measurement sites, the variation of the vehicles passing by the site, and the total amount of valid emission measurements. The tests' accuracy can be easily increased by larger sample sizes, and their representativeness by more measurement sites.

To date, remote sensing has primarily been used in Europe for research applications. However, with the clear need for improved real-world control of vehicle emissions, there are a number of areas where remote sensing could supplement existing regulatory emission test methods. The very large sample sizes obtainable with remote sensing mean the method is well-suited for market surveillance and fleet screening applications. These data would provide valuable emissions information to authorities and would help in the identification of vehicle models with poor or suspicious real-world performance. This could then direct the more rigorous, and costly, measurement methods such as PEMS and chassis dynamometer testing as part of market surveillance programs. Similarly, the short- and long-term effectiveness of, for example, promised emission improvements can be tracked over time. Remote sensing can in addition be used to identify high-emitting vehicles, detect individual tampering, and encourage proper maintenance of vehicle emission control systems.

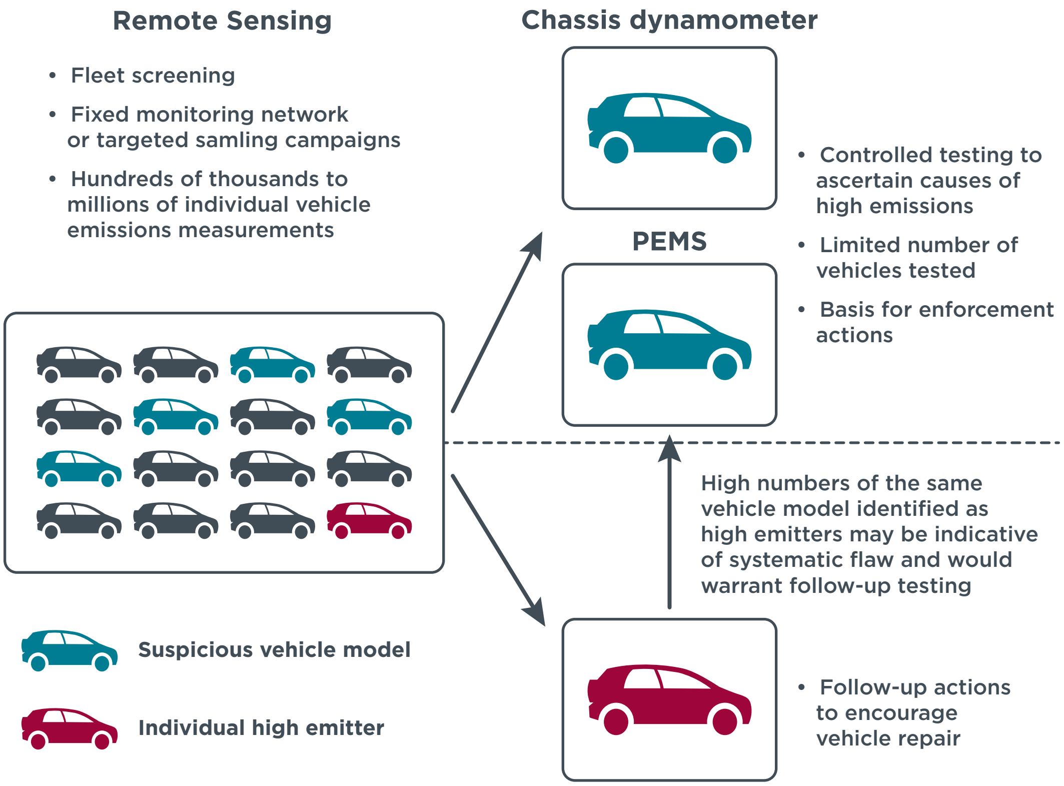

Figure ES1: Conceptual diagram showing the potential role of vehicle remote sensing in an enhanced European motor vehicle emission control program.

INTRODUCTION

Regulatory requirements have not been effective in controlling air pollutant emissions from light-duty diesel vehicles in Europe. Diesel cars have been complying with ever more stringent emission limits in the laboratory over a standardized test, but in real-world driving conditions, these same vehicles are emitting far higher amounts of nitrogen oxides (NO_x). These excessive NO_x emissions have contributed to nitrogen dioxide (NO_2) air quality values that persistently exceed limits in many European cities, and increased air pollution caused by these emissions has been linked to approximately 5,000 to 7,000 premature deaths each year in Europe (Anenberg et al., 2017; Jonson et al., 2017). The large discrepancy between in-use and type-approval emissions is at the heart of the so-called diesel emission scandal. It has also revealed severe shortcomings of in-use vehicle emissions surveillance.

These discrepancies have highlighted the need for strengthened emission test programs for both type-approval and in-use surveillance. Real-driving emissions (RDE) testing is therefore a key component of upcoming modifications to the European regulatory program for light-duty vehicles. Beginning in 2017, NO_x emissions from new vehicle types will be measured on-road, within strict boundary conditions, using a portable emissions measurement system (PEMS). The emission limit value will be reduced to 120 mg NO_x per km under RDE test conditions for all new vehicles by 2021. Close monitoring is needed to assess the degree to which this change in test procedure actually reduces exhaust emissions from the European vehicle fleet. RDE testing is being implemented alongside the introduction of a more challenging laboratory test protocol, the Worldwide Harmonized Light Vehicle Test Procedure (WLTP), and revisions to the existing type-approval and market surveillance framework.

As these changes are finalized, it is an opportune time to consider the role other real-world emissions test methods can play in an enhanced vehicle emissions monitoring program. This paper provides an overview of one such method, vehicle remote sensing, which has been applied for more than 25 years to measure emissions from in-use motor vehicles. To date, this method has—in the EU—primarily been used for research purposes and has not been incorporated into regulatory programs for the control of motor vehicle emissions. **In this paper, we review the technical details and applications of vehicle emission remote sensing and explore its potential in an enhanced European vehicle emissions monitoring program.**

VEHICLE EMISSION TEST REQUIREMENTS IN EUROPE

Broadly, current regulatory vehicle emissions testing occurs in three distinct phases of a vehicle's lifetime (see Figure 1). The theoretical goal of this test program is to make sure that the emissions are below specified limits throughout the vehicle's useful lifetime. The first phase of emissions testing occurs during a vehicle's type-approval process. Before a vehicle model can be certified for sale in the EU, its manufacturer must demonstrate that emissions of air pollutants from a representative prototype of the model are below regulated limits. This testing is conducted in a laboratory on a chassis dynamometer while the vehicle is driven over a defined test cycle, currently the New European Driving Cycle (NEDC). WLTP-based test procedures, including modified driving cycles, began to be phased in starting in September 2017 to replace NEDC-based testing. Conformity of production and in-service conformity testing are performed to verify the emissions performance of production line and in-use vehicles, respectively. These tests have also been performed in a laboratory using NEDC-based protocols, typically at manufacturers' facilities.

Unfortunately, the current design of the EU regulatory program for light-duty vehicle emissions is not, in practice, meeting the stated goals of EU motor vehicles emissions legislation. The NEDC-based type-approval process and current conformity of production and in-service conformity procedures, which also rely on the NEDC cycle, are not sufficiently controlling real-world pollutant emissions, particularly for diesel vehicles. Weaknesses of the current program are well documented (Mock & German, 2015; Muncrief, 2016; EP, 2017a); they include:

- The NEDC cycle is not representative of operating conditions typical of real-world driving. The NEDC includes little transient operation and does not adequately cover high engine load operation. Most importantly, vehicle manufacturers have chosen to focus effective NO_x emission controls for diesel cars/vans to the prescribed conditions of the NEDC, yet have compromised emission controls on-road.
- Post type-approval emissions verification testing is generally weak. Conformity of production and in-service conformity testing is conducted on a limited number of vehicles, typically at manufacturers' facilities, with an accepted failure rate of more than 50%, unrepresentative engine loads, and overreliance on vehicle on-board sensors.
- There is a lack of a reliable market surveillance system, and no provisions are in place for independent confirmatory or in-service testing.

As a consequence, light-duty diesel vehicles emit several times higher NO_x emissions on the road than under type-approval conditions; even current Euro 6 models emit, on average, 4.5 times more under real-world conditions than their laboratory-based type-approval limit (Baldino et al., 2017).

As mentioned above, actions are underway to address the deficiencies of the NEDC-based vehicle emissions test process. Laboratory WLTP-based testing and RDE test NO_x limits for type-approval began to be phased in starting in September 2017. A fourth and final package of the RDE legislation is currently under development, and is expected to extend RDE requirements to in-service conformity testing (Mock, 2017). Finally, the European Parliament and Council are negotiating an overhaul of the current type-approval and market surveillance framework.

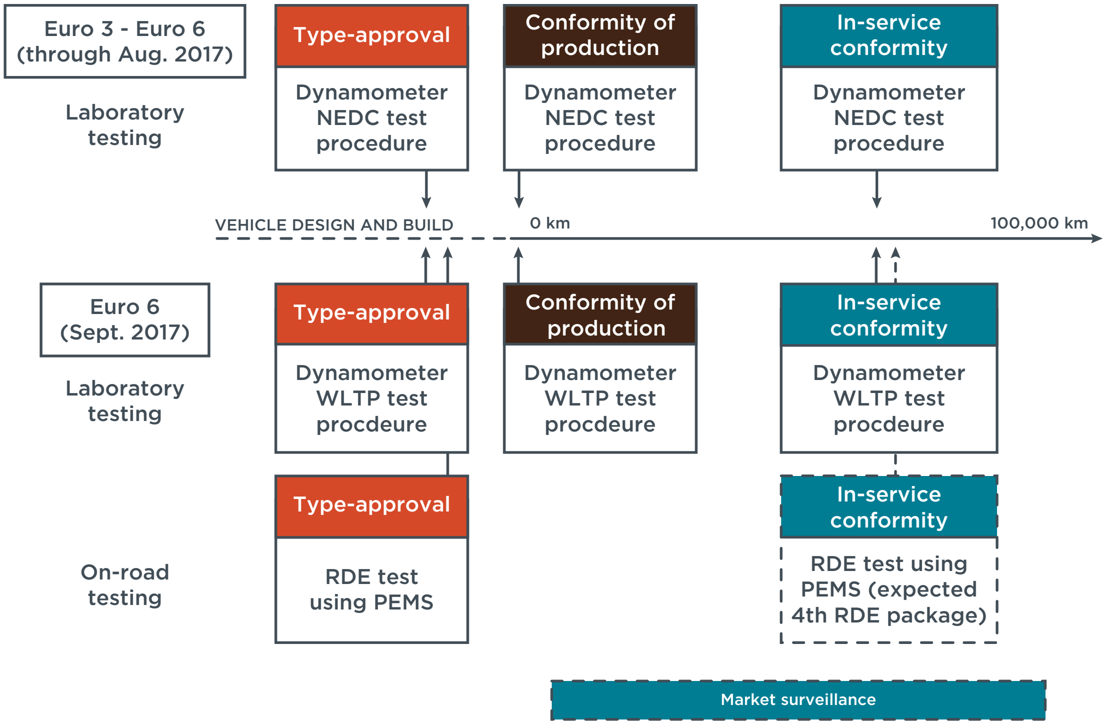

Figure 1: Overview of current and future vehicle emissions test requirements in the EU.

The introduction of WLTP-based laboratory testing and RDE testing using PEMS is expected to reduce disparities between type-approval and real-world emissions. However, experience with the past three emissions regulations calls for caution and closer monitoring. For example, the RDE procedure, like laboratory testing, is a standardized test with specified test conditions and protocols, albeit less prescribed in the exact sequence of driving states. Furthermore, the emissions measurement equipment physically interacts with the vehicle undergoing testing. While the real-world nature of the RDE test inherently makes it more randomized than laboratory testing, the risk remains that emission control strategies could be optimized for the RDE test and not for the full range of vehicle operating conditions. Similarly, there are open questions regarding how closely RDE test conditions—including speeds, accelerations, gradients, and temperature—match normal on-road driving conditions. It is also unclear whether PEMS testing alone can be efficiently applied to cover the expanded scope of the proposed market surveillance framework. This is expressed for instance by the call from the European Parliament urging "the Commission and the Member States to establish remote fleet monitoring schemes […] to screen the environmental performance of the in-service fleet" (EP, 2017b).

A fundamental weakness in the existing and proposed testing protocols is the pre-defined set of conditions, such that the test vehicle can sense that an emissions test is underway. The aim of real-world testing should be to measure emissions under conditions when the vehicle cannot detect the presence of an emissions test.

Vehicle remote sensing differs from all previous regulatory testing protocols in that the vehicle undergoing testing is separated entirely from testing equipment. This greatly limits the potential for vehicle engineers to design systems to detect emissions testing.

Furthermore, there are no prescribed driving conditions; emissions are measured as vehicles are driven on actual roadways by their owners.

In the following sections, we review technical details and applications of vehicle remote sensing, and explore the potential for its use in an enhanced European vehicle emissions monitoring program. Our objectives are to provide a clear assessment of the current state of the remote sensing technology, describe the types of emissions analyses that can be conducted with remote sensing data, and highlight areas where remote sensing could supplement emission test methods currently used in the EU light-duty vehicle regulatory program.

REMOTE SENSING: TECHNICAL BACKGROUND[1]

The remote sensing (RS) technique measures exhaust emissions by absorption spectroscopy without interference with the vehicle, its driver, or the driving. We first describe the remote sensing instrument configuration as developed since the late 1980s (Bishop et al., 1989). In this configuration, the instrument is placed next to the road and consists of three coordinated units, as illustrated in the top panel of Figure 2[2]. The purpose of each unit is:

- The first unit measures vehicle emissions by absorption spectroscopy. Sources of infrared and ultraviolet light are placed next to the road with their beams directed across the road at the height of the vehicle tailpipe or the exhaust plume. The light is reflected back by a mirror located at the other side of the road and focused into a detector. The measured attenuation of the light is directly proportional to the concentration of certain pollutants in the atmosphere. These pollutants come from the exhaust of the vehicle that has just passed, as well as from the background presence of the species in the ambient air. Therefore, the pollutant concentration that was measured before the vehicle crossed the light beam is taken as background pollution and subtracted from the measurement. This difference is ascribed to the exhaust of the vehicle that has just passed by. Each valid record is the average of ten to 25 valid concentration measurements taken at a sampling rate of 100 Hz within 0.5 seconds of the vehicle's passing. If certain quality parameters are met, the average concentration increment is retained. The same is done with the concentration of carbon dioxide (CO_2) in the plume. The CO_2 increment is directly proportional to the fuel burned in the engine of the vehicle, and thus to the amount of fuel consumed. CO_2 and air pollutants are subject to the same dilution and dispersion conditions, and hence it is meaningful to take their ratio. This ratio is the instantaneous emission rate expressed in units of grams pollutant emitted per kg of fuel burned for each vehicle measured. The instrument is regularly calibrated against a puff of gases of known concentrations.
- The second unit measures speed and acceleration of the vehicle a bit upstream of the emission measurement[3]. Speed and acceleration provide a measure for the vehicle's engine load, conventionally expressed as vehicle specific power (VSP) (Jimenez-Palacios 1998). This load is associated with the instantaneous emission rate.
- The third unit, a camera, records the number plate of the vehicle. Thus, technical data for the vehicle can later be accessed from the vehicle registration database. Most important are the certified emission standard or the year of first registration, the fuel type, the rated engine power, the gross vehicle weight, the vehicle make and model.

These three units combined provide the emission rate, in grams of pollutant per kilogram of fuel consumed at a certain engine load, for a vehicle whose technical characteristics are known from the vehicle's registration data. The technology has been officially acknowledged by the US Environmental Protection Agency for use in vehicle exhaust emission measurements and air quality management (US EPA, 1996; 1998; 2002).

---

[1] This chapter follows in large parts the earlier ICCT guidance note on remote sensing (Borken-Kleefeld, 2013).

[2] We describe here the principal set-up of an RSD instrument as pioneered by Bishop & Stedman and as commercialized by companies AccuScan, Envirotest, and lately Opus.

[3] For a recent validation of its accuracy, cf. Rushton et al., 2017.

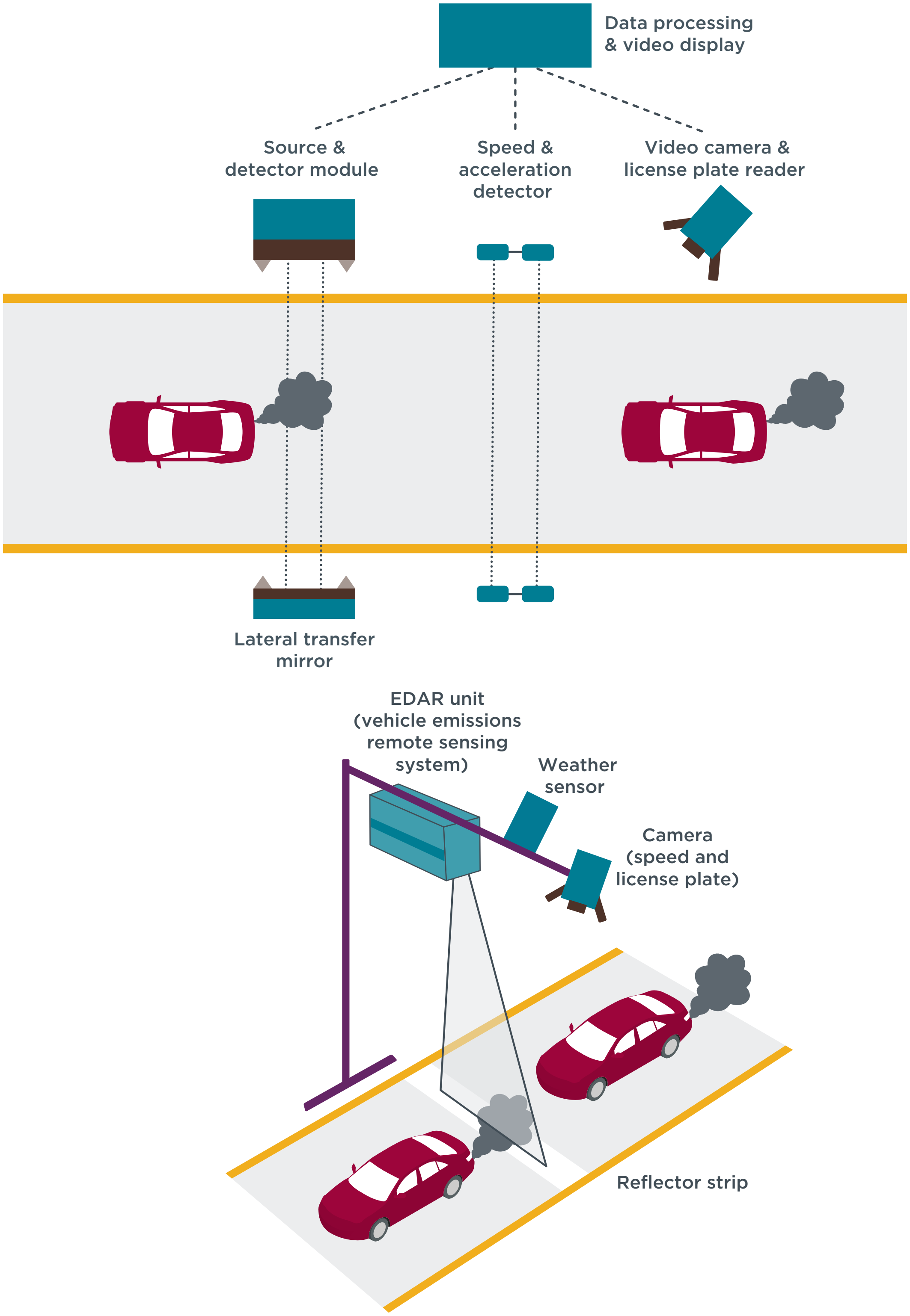

Figure 2: Schematic setup of the three units of the remote sensing device. Top, setup for cross-road remote sensing: the light source with the reflecting mirror at the other side of the road and the light detector; the speed and acceleration detectors; and the number plate recorder (McClintock, 2012). Bottom, setup for top-down remote sensing system (EDAR) (Ropkins, 2017).

A new remote sensing instrument (EDAR[4]) has been developed since 2009 that expands on the above principles. A laser is used as the light source, making the measurement more selective and precise to the pollutant(s) under study. In addition, the light source and detector are mounted above the road in this configuration, with the beam looking down instead of across the road. The laser light is scattered back from a reflector strip installed on the road's surface. The laser beam sweeps the whole breadth of the road and has a 20,000 Hz sampling rate. Thus, the exhaust plume is captured in its entirety, and all molecules in the plume can be measured (US Patent No. 8,654,335 B2, 2014). The measured attenuation of the laser light is proportional to the pollutant concentration. The concentration measured beside the vehicle or just before the vehicle crosses the beam is subtracted as background pollution, and the remaining difference is ascribed to the vehicle exhaust. This allows for an absolute measurement of the pollutants emitted when passing the sensor. The overhead configuration with sweeping beam captures the exhaust pollutants independent of the exact tailpipe location. In addition, this geometry makes it easier to conduct measurements at sites with multiple lanes and/or denser traffic. Speed and acceleration are measured, and a physical image of the vehicle and its number plate are recorded.

Validation exercises for the EDAR instrument have demonstrated a very high accuracy for measuring pollutant concentrations (DeFries, 2016). Pilot applications in the United States and United Kingdom have confirmed the suitability of this new instrument for on-road emission measurements (Ropkins et al., 2017). Further peer review is progressing, as are software and hardware developments.

POLLUTANTS COVERED BY REMOTE SENSING INSTRUMENTS

Current standard remote sensing instruments[5] can determine carbon monoxide (CO) and dioxide, propane, nitrogen oxides (NO, NO_2) as well as opacity in the infrared and ultra-violet spectra. Some research instruments (FEAT) can additionally measure emissions of ammonia (NH_3) and sulfur dioxide (SO_2)[6]. The new EDAR instrument uses laser light. This allows determining the standard pollutants above with much higher accuracy. In addition this instrument can be tuned to measure various specific hydrocarbons such as methane (CH_4) and ethylene (C_2H_4) (Ropkins, 2017). Typically, the measurement output is the ratio to the measured CO_2 increment or the amount of fuel consumed, which is directly proportional using the carbon weight fraction of gasoline and diesel fuels.

The NO over NO_2 fractions vary strongly depending on aftertreatment technology and driving situation (Carslaw et al., 2016). Their simultaneous measurement is needed for an accurate determination of total NO_x emissions, and in particular in places with NO_2 air quality problems. Opacity gives some information on black carbon contents in the exhaust; this is, however, not equivalent to mass or number measurements of particulate matter as prescribed under type-approval testing. Current remote sensing instruments are not capable of measuring instantaneous CO_2 emission rates.

---

[4] The EDAR instrument is developed and commercialized by HEAT LLC.

[5] RSD 5000 generation commercialized by Envirotest/Opus Inspections. The earlier generations (RS 4600 and older) did not measure NO_2.

[6] FEAT device by University of Denver, e.g.: Bishop et al., 2012.

VEHICLE CATEGORIES COVERED IN REMOTE SENSING CAMPAIGNS

The remote sensing technique is not limited to a certain vehicle category. The only requirement is that the measurement beam crosses the exhaust plume. This means that the traditional across-road instruments need to be adapted to the geometry of the exhaust pipe. For practical reasons, mostly vehicles with horizontal exhaust pipes within a few dozen centimeters above ground have been measured, meaning light-duty vehicles have been most extensively measured around the globe (Bishop & Stedman, 2008; Carslaw et al.; 2011; Mazzoleni et al., 2004; Zhang, Bishop, & Stedman, 1994; Sjödin & Jerksjö, 2008; Goetsch, 2013). Results for light-duty vehicles are therefore the focus of this review. Nonetheless, there have also been measurements of heavy-duty trucks and buses, motorcycles, and motor-rickshaws (Burgard et al., 2006; Yanowitz, McCormick, & Graboski, 2000). Furthermore, the optical system has been adjusted to measure exhaust pollutants from snowmobiles, aircrafts, ships, locomotives, and non-road machinery[7].

The exact geometry of the exhaust pipe is not relevant for the new EDAR instrument. As its beam sweeps the whole breadth of the road, the instrument can capture the exhaust plume in its entirety, largely independent of the exact location of the exhaust pipe. Thus, with the same configuration, it can in principle measure emissions from light- and heavy-duty vehicles as well as motorcycles (Hager Environmental, n.d.). This setup is an improvement in the ease of use and hence the practical capture of the fleet. The EDAR instrument maps the origin of the pollutant emission on a 2D image. This has also been used to locate the source of evaporative emissions (Kishan, 2017).

DRIVING CONDITIONS COVERED—SITE CHARACTERISTICS

The location(s) for the remote sensing measurement(s) determine(s) the range of observable driving conditions, and thus the observable range of emission rates as a function of engine loads. Previous remote sensing studies have found that driving conditions are very variable, even at a single location. Therefore, even single sites usually cover a wide range of engine loads, so that the average emission rate is based on a broad operating window. For example, Figure 3 compares observed vehicle speed and acceleration from a single remote sensing sampling site outside Zurich (Gockhauser Strasse) with the urban portion of the Common Artemis Driving Cycle, widely used in Europe for simulating real-world driving conditions in chassis dynamometer tests. With the exception of very low speeds, the single Zurich site provides coverage of operating conditions similar to what is found in the standardized test cycle.

Nonetheless, it is often advisable to measure at several sites to cover a wider range of driving conditions and a broader cross-section of the fleet in the area under investigation. We can safely conclude that (decent) emission measurements by remote sensing capture a wide range of driving conditions; thus the ensemble of instantaneous emission rates from a large cross-section of vehicles can be compared to the average emission rate(s) from longitudinal emission tests over chassis dynamometer cycles or RDE trips. Care should, however, be taken to limit the comparison to emission rates measured at similar engine loads.

---

[7] G.Bishop, D. Stedman, and collaborators. See reports: http://www.feat.biochem.du.edu/Nonroad_vehicles.html

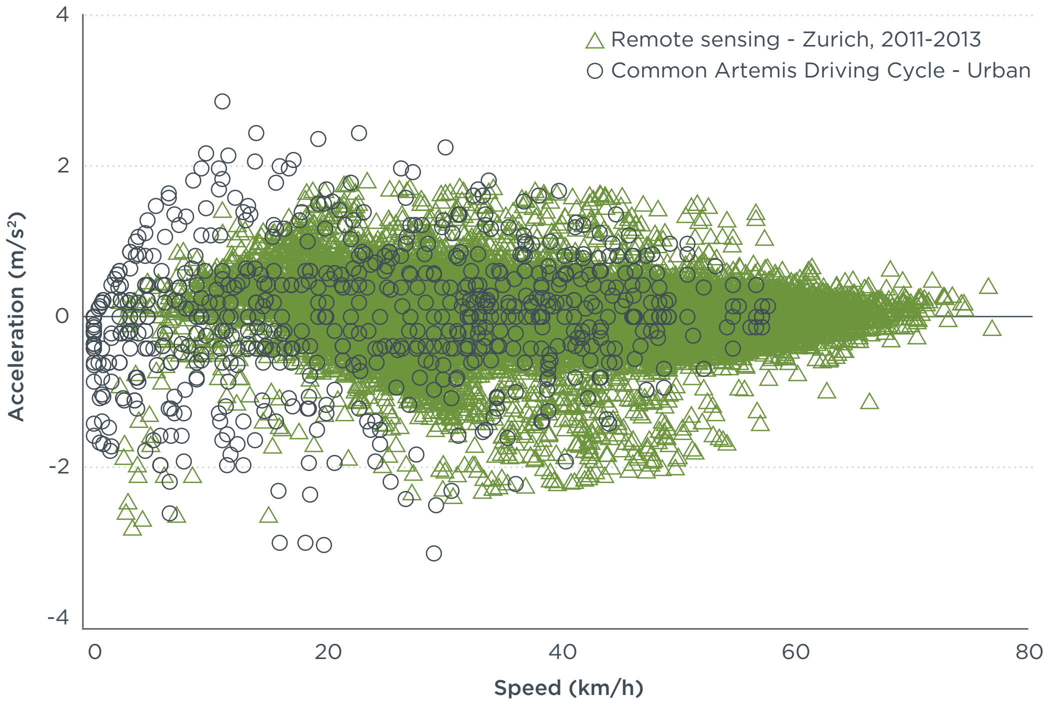

Figure 3: Driving conditions observed at a measurement location on the outskirts of Zurich compared to the urban portion of the Common Artemis Driving Cycle.

Data pool: About 65,500 valid records collected from 2011 to 2013 outside Zurich (Chen & Borken-Kleefeld, 2014)

Two distinct driving conditions are outside the scope of remote sensing measurements. As a function of their design, remote sensing instruments only measure emissions from moving vehicles, and emissions at idle or very low speeds will be discarded. In practice, this is not a relevant limitation, as pollutant emissions are low when the engine is not under load. Moreover, the emission rates from remote sensing are normalized to the fuel consumed; this accounts hence for the low load. In fact, for instance, for Euro 3 and Euro 4 diesel cars the difference of the (fuel-based) NO emission rate at negative VSP compared to the average emission rate is only a few percent for NEDC like engine conditions (Rhys-Tyler & Bell, 2012).

Furthermore, emissions after a cold start (or a hot start, for that matter) cannot be clearly distinguished from running emissions. However, a clever choice of the measurement location, such as at the exit of a long-term parking lot for cold-start emission rates, or at a highway exit for hot emissions, can be used for this specific investigation. Both aspects need to be considered when comparing in detail with emission measurements, e.g., from chassis dynamometer or on-road measurements. The EDAR instrument is in addition capable of measuring exhaust temperature.

For a high rate of valid remote sensing measurements, a few provisions should be respected, notably (McClintock, 2012):

» The measured concentration increments can only be ascribed to individual vehicles, when these are clearly separable; therefore, single lane traffic is often preferred. With the top-down configuration of the EDAR instrument, emissions from traffic on multi-lane roadways can also be measured.

- Free-flowing traffic is preferred, steady acceleration would be optimal. Sites where vehicles accelerate onto a motorway or uphill or from a stop sign or from traffic lights are good.
- The engine should be under load, hence a positive acceleration or some small road gradient are desirable.
- Low probability of cold-start vehicles passing by, to exclude false detection of high emitters (particularly relevant for gasoline cars).

When the objective is to determine emission rates during urban and moderate driving conditions, similar to the homologation test cycles, then sites with typical urban driving are needed. When conducting research, such as on the emission rates during aggressive driving (or so-called "off-cycle" emission rates), then the above restrictions do not necessarily apply. Ultimately, the objective of the sampling determines the suitability of the site.

The measurements are usually performed during daytime, when traffic is most intense, but the system also operates well at night. A dry, non-dusty road is preferred, meaning a small limitation for operating conditions. For recommendations on careful system setup and quality assurance, consult the extensive US EPA remote sensing guidance documentation (US EPA, 2002).

HOW IS A RS CAMPAIGN CARRIED OUT IN PRACTICE?

A remote sensing campaign is usually carried out in four steps:

- Site selection and traffic management authorizations: A suitable road site must be found. In addition to the measurement conditions listed above, there are a number of practical concerns that need to be addressed: sufficient space for the equipment, safe passage for the personnel during setup and calibration, requirements from traffic flow, etc. Depending on the local situation the search for a suitable site and all necessary authorizations may take quite some preparation.
- Setup and calibration of the instrument as well as actual measurement: The instrument's three distinct units need to be carefully adjusted. The light beams need to be aligned with the mirror and with the height of the exhaust plume of the vehicles targeted. The speed measurement bar needs to have its signal at the height of the wheels. And finally, the camera must be adjusted to capture the back number plate well. These settings need to be checked during the course of the measurement campaign. More importantly, because of instrument drift, it is necessary to calibrate the light-detector unit about every two hours with certified gas canister samples. The observed drift can be about ±10% between two calibrations. The instrumentation must be safely placed and traffic not obstructed. In particular, drivers should not be inconvenienced by the measurement setup in a way that would disrupt normal driving behavior. When the setup and calibrations are completed, emissions from passing vehicles are measured. These issues seem to be much less important with the EDAR instrument due to its overhead placement and an effective self-calibration (Ropkins, 2017). This means that EDAR can operate all day and unmanned.
- Data processing: This step includes data validation and cleaning and adding technical information from number plate records. Most of the work at this step involves transcribing number plates, which can be done using automated systems

or manually, and then matching these records with the registration data. In addition, recorded emissions data, speeds, and acceleration are checked for quality and corrected by the observed drift as necessary.

- Data analysis: Numerous examples of remote sensing data analyses are given in the main body of the text below—average emission rates for the fleet, by vehicle class and emission standard, by age, by driving mode, by temperature, etc.

Typical remote sensing campaigns have collected on the order of 10,000 to 200,000 valid records within a couple of days or weeks.

LIMITATIONS

The application of vehicle remote sensing has a few limitations:

- Remote sensing works most accurately under slight acceleration, e.g., uphill roads; therefore, emissions during idle and deceleration are not captured.
- Measurements are more difficult to make when raining or on a wet surface.
- Privacy concerns about number plate recognition need to be addressed in each case.
- Vehicle technical data are taken from the registration database. They record the technical features of the vehicle when new, but do not specify their actual state at the time of the remote sensing measurement. Yet, while this introduces uncertainty about the proper performance of an individual vehicle's exhaust aftertreatment system, it does reflect the actual fleet situation: The vehicle is obviously driven in the state it is measured and emits as much as recorded at the time of passing the beam.
- Evaporative emissions do not correlate with carbon dioxide emitted from fuel combustion. While it is harder to locate the exact source of evaporative emissions, any lack of correlation with CO_2 emissions points to a leakage that could warrant closer follow-up inspection of the individual vehicle or possibly the class of vehicles in regular cases.

CONOX PROJECT – ANALYSIS OF PAN-EUROPEAN REMOTE SENSING MEASUREMENTS

Remote sensing measurements have been conducted in Europe since the early 1990's, notably in Sweden, Switzerland, the UK, Spain and France (see Appendix: "Overview of remote sensing campaigns in Europe since 1991," for details of these studies 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 2012 have been pooled together in 2017. This common data pool, currently consisting of 750,000 records, has an unprecedented scope allowing for much more comprehensive analysis with high statistical significance. This analysis is ongoing and contributes to tracking the emission behavior of individual manufacturers, their engine families and car models.

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, grams of pollutant per kilogram of fuel consumed, and the cycle or trip-based measurement unit, grams of pollutant per kilometer traveled. Both units are related by the fuel consumption rate at the respective engine load(s). This fuel consumption rate is either adjusted from measurements under average driving or modeled for the specific ensemble of instantaneous engine loads as actually measured during the remote sensing. The former method is rather straightforward but coarser, while the latter requires much more data.

This second method allows for a quite detailed comparison with, for example, full PEMS trips or chassis dynamometer cycles: These trips or cycles can be considered as a succession of engine loads over time, and the resulting emission factor is the total pollutant load over the distance (potentially with some sophisticated weightings if the Euro 6 RDE protocol is applied). The instantaneous emission rates per engine load can also be sourced from remote sensing measurements and the total trip can be synthesized with these input data.

If the synthesized result were to be much higher than, for example, emission rates from homologation testing, then this would strongly suggest this vehicle (model) for further investigating, similar as on-road NEDC emissions of Euro 5 diesel cars are already much higher than chassis dynamometer NEDC emissions. See Rhys-Tyler and Bell 2012; Degraeuwe and Weiss 2017, and CONOX methodology report (forthcoming).

REMOTE SENSING: TYPICAL APPLICATIONS

Vehicle emission remote sensing has been deployed in the United States since the late 1980s, and since the 1990s in Europe and other parts of the world. This section summarizes results of remote sensing campaigns in various places[8], illustrating typical research approaches and data products. Remote sensing measures an instantaneous emission rate of *individual vehicles* as they pass by the instrument location. Hence there are many options for data aggregation and analysis. The reliability of the results depends to a large extent on the overall sample size. This can be determined by the number of measurement days. The choice of the site determines the scope of vehicles measurable as well as the representativeness of the measurements for a wider area. Both can be increased by using multiple sites. We present examples mostly for NO_X emission rates, but the same principles would also apply to the other pollutants measured by remote sensing.

In the following, we proceed from a coarse to a fine analysis, as illustrated in Figure 4; remote sensing can typically answer questions relevant for:

1. **Air quality monitoring, planning, and vehicle emission models**: What is the average emission rate for the fleet, for different vehicle types, by emission standard, under real-driving conditions, and at different traffic locations, as well as their development over time?
2. **In-use surveillance**: What is the average emission rate by manufacturer and by model under real-driving conditions for statistically representative samples? What is the long-term durability of exhaust aftertreatment systems?
3. **Vehicle inspection and maintenance**: Does an individual vehicle have suspiciously high pollutant emissions in real driving? Or, inversely, is this vehicle's aftertreatment well maintained and can it be exempted from vehicle inspection?

---

[8] Results are mostly presented for remote sensing campaigns in Europe, but similar analysis has been done in the US and other places around the world. For an overview of US and global research activities, consult the website of the developers (http://www.feat.biochem.du.edu/pub_list.shtml); an overview of remote sensing campaigns in Europe since the 1990s is given in the Appendix.

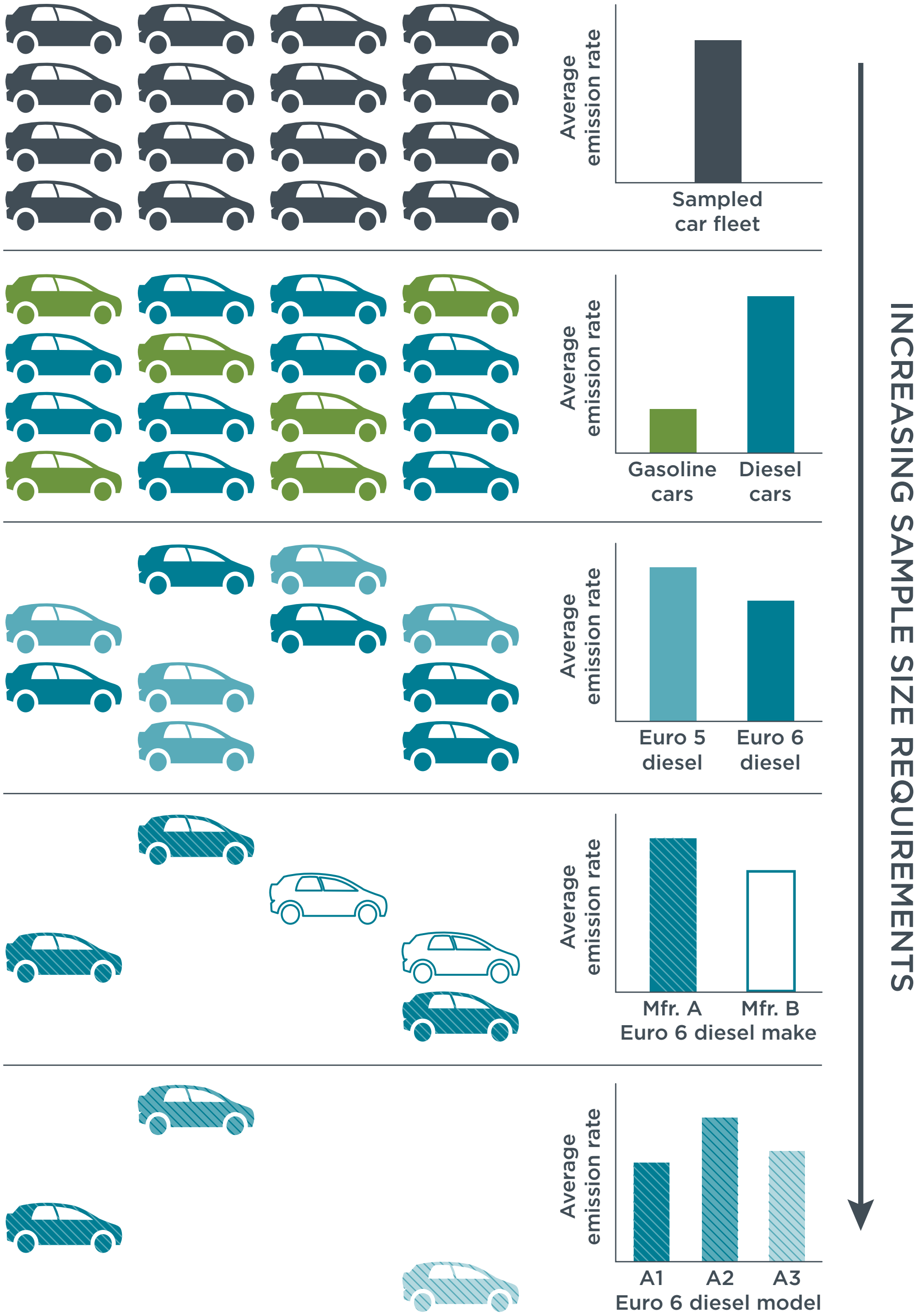

Figure 4: Remote sensing emission measurements can be analysed from the coarsest to the finest level, depending only on sample size and the availability of extra vehicle information, e.g., from the vehicle registry. The top level looks at the average emission rate of the fleet of vehicles as they pass by, passing through a finer disaggregation by vehicle type, emission standard, by manufacturer and possibly aftertreatment technology. Not shown: possible analysis by vehicle category, vehicle age, driving condition, temperature, high emitter identification, or clean screening.

REMOTE SENSING FOR AIR QUALITY MONITORING, PLANNING AND VEHICLE EMISSION MODELS

What is the average emission factor for the fleet?

At a broad level, a key question for air quality planning relates to the average emission factor for a fleet of vehicles in a given area. In practice, these data are difficult to obtain in the real world, and model calculations are predominately used to calculate vehicle emission contributions to air pollutant emission inventories. With vehicle remote sensing, emission rates from thousands of in-use vehicles can be measured in a single day at the selected sampling location, allowing for the direct evaluation of fleet-average pollutant emission rates.

The average overall records of a remote sensing campaign can be considered the average emission rate of the fleet of vehicles measured at the specific site and time. When the measurement period and the location are well chosen, results are also representative for different times and a wider area. This assertion can be made firm by either continuous measurements, repeated measurements during selected periods, and/or choosing several different measurement sites in the area under consideration.

Experience shows that the most important determinants for the fleet-average NO_X emission rate are the fleet mix and the driving condition. For instance, a high share of buses or trucks typically increases the fleet-average NO_X emission rate at a location. Similarly, locations with higher speeds (or gradient) typically have higher NO_X emissions than others.

An example of how fleet-average emission rates can vary within in an urban area is shown in Figure 5, which presents NO_X emission rates measured using remote sensing at four different urban sites in London in 2012 (Carslaw & Rhys-Tyler, 2013). Queen Victoria Street, Aldersgate Street, and Greenford Road are urban streets with similar mean driving conditions. They differ notably in the share of buses and taxis, which heavily affect the share of diesel vehicles. The higher the share in diesel vehicles, the higher the average (fuel-based) NO_X emission rate. The share in primary NO_2 emissions is about 15% on fleet average across all sites[9].

While not shown here, the vehicle fleet mix has a large influence on other pollutant emission rates as well. Remote sensing can reveal the emission differences between fleets and different sites.

---

[9] NO and NO_2 were measured separately.

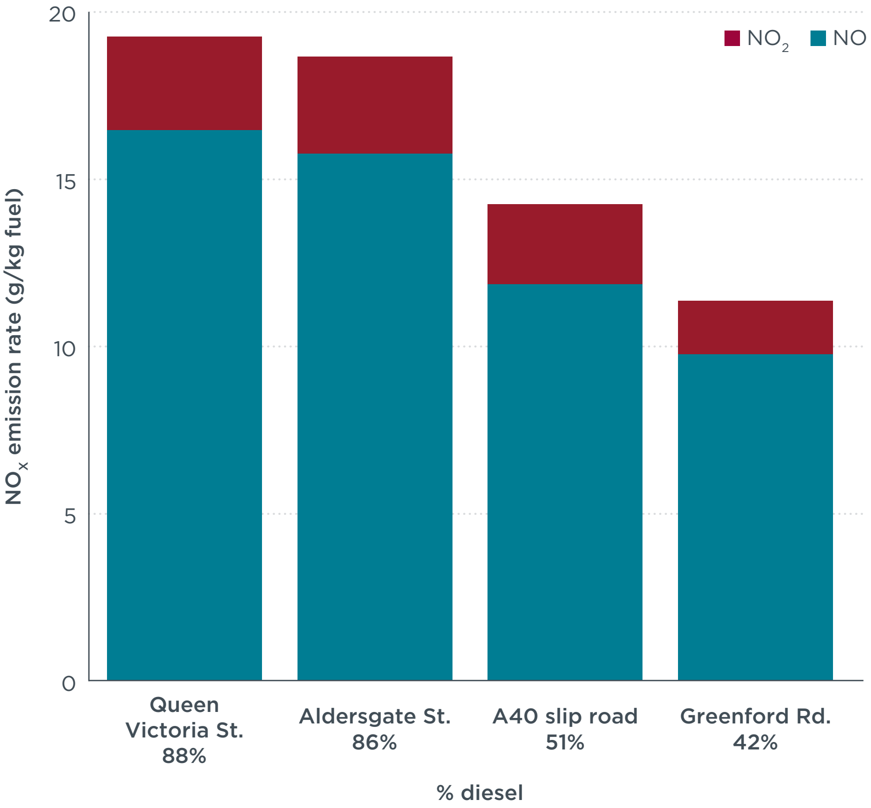

Figure 5: Fleet-average NO$_x$ emission rate at four different streets in London, 2012 (Carslaw & Rhys-Tyler 2013), illustrating the influence of fleet composition. Percentages indicate the share of diesel vehicles at each location.

Data pool: Almost 70,000 valid records measured at the four London locations during six weeks in 2012.

The detailed information about the composition of the in-use fleet comes as a valuable by-product of the emission measurement. It is essential information for traffic management and traffic emission modeling. The more representative the measurement site and the vehicles captured, the more useful the traffic information is in describing the vehicle population in a larger area.

What is the average emission factor per vehicle category?

Remote sensing data can also be aggregated to provide average emission rates for specific vehicle types, enabling separate investigation of emissions from, for example, gasoline and diesel cars. The average emission rate per vehicle category is assessed in the same way as for the overall fleet average. Remote sensing measures the emissions of the vehicles on the road as actually driven, without any need for assumptions about the mix by vehicle age and size. As before, the representativeness can be increased by measurements at different sites, thus capturing a different fleet and different driving conditions.

Figure 6 shows the average NO$_x$ emission rate by vehicle type from the same 2012 remote sensing campaign in London. Clearly, only gasoline cars have NO$_x$ emissions below the fleet-average—or, in other words, NO$_x$ emissions from the on-road fleet are determined by the diesel vehicles, notably the diesel cars and heavy-duty vehicles. As mentioned above, the share of diesel cars, taxis, and heavy-duty vehicles in the fleet determines the resulting NO_x emission level at different locations. The NO_x emission rates for diesel cars by emission standard as measured in 2012 in London are shown in the right panel of Figure 6. The data clearly illustrate that the progression from Euro 1 to Euro 5 standards did little to improve the real-world NO_x emissions performance of diesel cars, despite a decrease of type-approval limits by more than 80%.

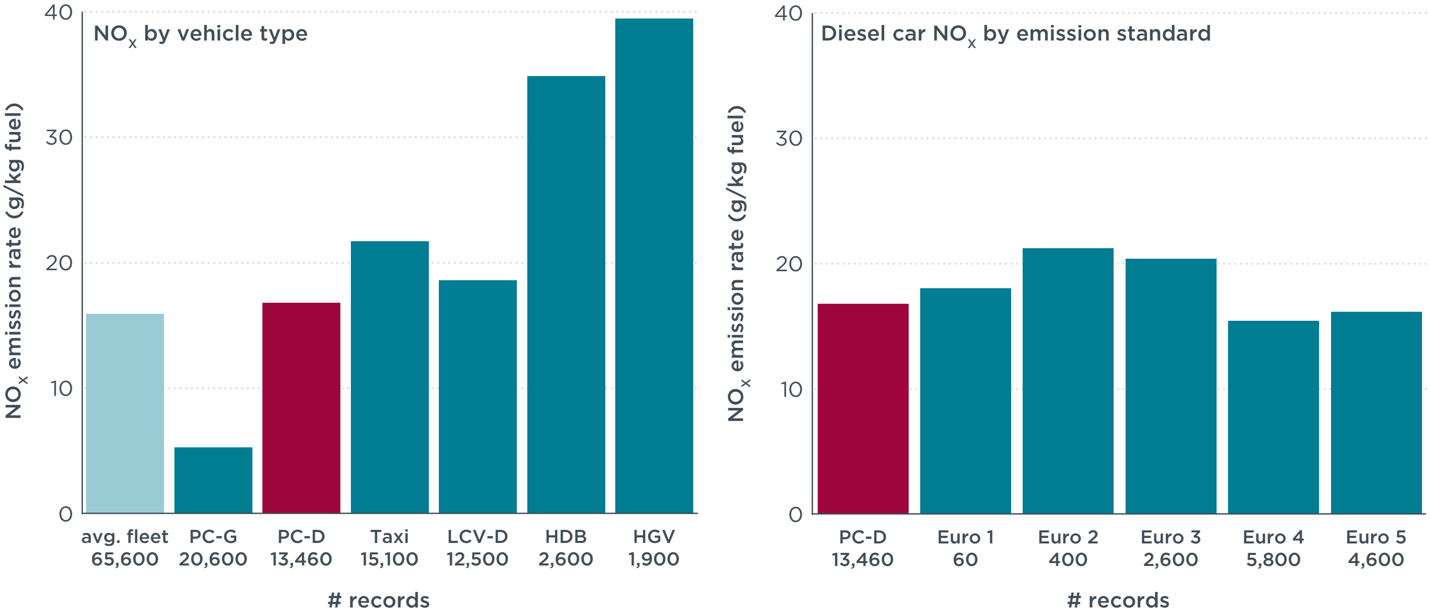

Figure 6: Average NO_x emission rate per vehicle type (left) and from diesel cars by emission standard (right) as measured in London in 2012 (Carslaw & Rhys-Tyler, 2013). The fleet average is dominated by diesel vehicles. Emission rates from diesel cars have not significantly reduced from Euro 1 to Euro 5 emission standard, i.e., from 1992.

Abbreviations: PC-G/D: Passenger car gasoline/diesel; LCV-D: Light commercial vehicle diesel; HDB: Heavy-duty bus; HGV: Heavy goods vehicle.
Numbers below the label indicate the number of valid records. Data pool: Almost 70,000 valid records measured at the four London locations during six weeks in 2012.

What is the average emission factor by emission standard?

To determine the average emission rate per emission standard, the certified emission standard of the sampled vehicles or, as closest proxy, the first year of registration is needed. This information is usually supplied from the vehicle registry through the number plate of the vehicle. Figure 7 (left) shows the average NO_x emission rate from diesel cars during the remote sensing campaign in London in 2012. The individual emission records are simply aggregated by vehicle category and emission standard. Such information is needed to monitor how much emission reductions prescribed by successively more stringent emission standards materialize in on-road driving. In addition, such data has been used to validate and refine traffic emission models like COPERT (Ekström, Sjödin, & Andreasson, 2004), HBEFA (Keller et al., 2017), the UK National Atmospheric Emission Inventory database of emission factors for transport (Carslaw et al., 2011), or the Dutch VERSIT traffic emission model (van Zyl et al., 2015).

For diesel cars, NO_x emissions have actually been increasing in real driving since the mid 1990s, although limit values have become more and more stringent over time (Figure 7, right). This discrepancy between laboratory testing and on-road emissions is at the heart of the scandal around diesel cars employing defeat strategies. Note that the emission rates as measured in London or Zurich are averages over all brands. The high average emission level indicates that many manufacturers are producing cars with high on-road NO_x emission rates. It is also important to note that the on-road emission rate of gasoline cars follow emission limits very closely. Measurements in Switzerland were conducted at the outskirts of Zurich on an uphill road, ensuring emissions from hot engines under load. Because of the 9% gradient and 50 kph speed limit, the average engine load at the site is much higher than under the prescribed test cycle conditions.

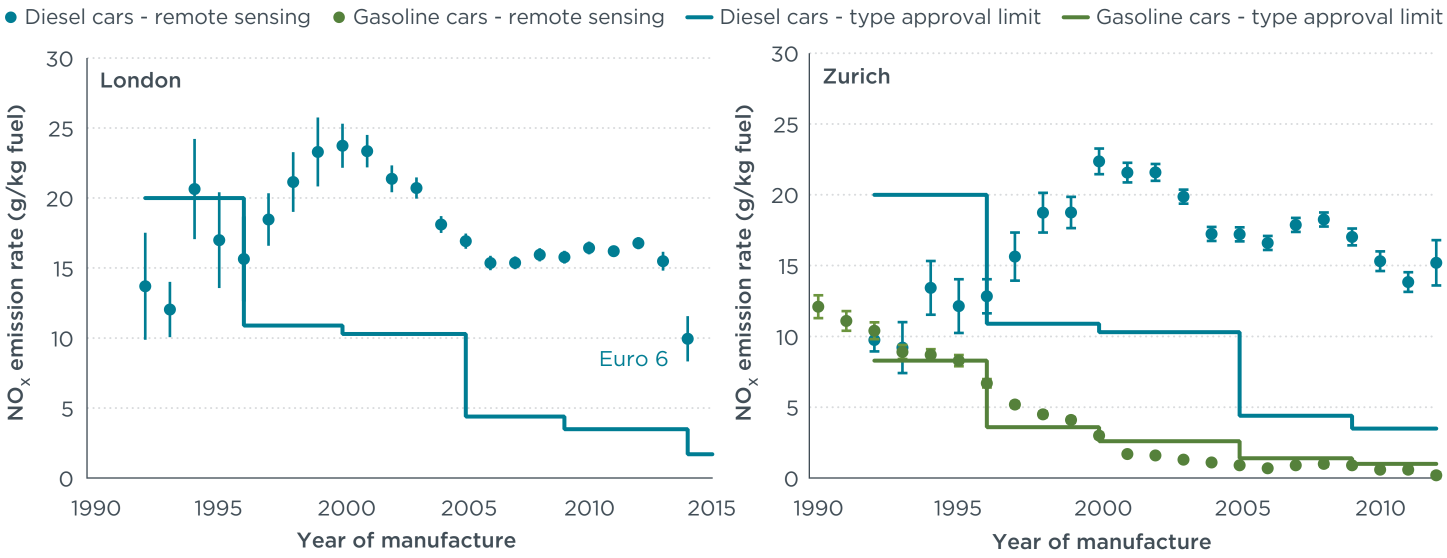

Figure 7: NO_x emission rates of diesel cars by year of manufacture from remote sensing campaigns in (left) London, 2012 and 2013 (Carslaw & Rhys-Tyler, 2013; Carslaw, 2014) and (right) Zurich, 2000—2012 (Chen & Borken-Kleefeld, 2014). The discrepancy between on-road emissions and the type-approval limit values is at the heart of the diesel NO_x emission scandal.

Data pool from London: 105,000 valid records obtained over six-week campaigns in London in both 2012 and 2013, some 20% of which are diesel cars.
Data pool from Zurich: 129,000 valid records obtained in 13 annual campaigns of about 15 days each in Gockhausen/Kanton Zurich from 2000 to 2012, some 14% of which are diesel cars and 86% gasoline cars.

The vehicles passing the remote sensing measurement site represent a mix of different ages and mileages even within the same emission standard. Hence, it is possible to compare and follow how the emission rate develops with age and thus to measure the durability under real driving conditions. The European emission standards span about five model years each; therefore, a single campaign can only reveal deterioration over this interval. When the measurements are spaced over a larger interval, it becomes possible to monitor the durability over a longer period. That is an important component for any in-use surveillance program and will be discussed further below.

What is the average emission factor by driving mode?

A sample of tens of thousands of vehicle emission records comprises a wide range of driving conditions, characterized by speed and acceleration, even when taken at a single location only. Typically, driving conditions observed on the road cover a (much) wider range and are more dynamic than standard test cycles, be it the ARTEMIS cycles (Andre, Hammarstrom, & Reynaud, 1999) or the forthcoming WLTP, let alone the NEDC. Thus, the average over the ensemble of several thousand instantaneous emission rates from remote sensing is comparable to an emission rate averaged over a test cycle or test trip with a few thousand second-by-second readings. The key difference between the two aggregates is how often which engine conditions were met, i.e., the weighting of the individual emission rates. Therefore, when the two averages are to be compared it is important to filter for similar engine loads, thus having at least equal average loads in the end. A conversion algorithm between instantaneous RS emission rates and various test cycles has been developed within the CONOX project.

The key advantage of remote sensing with this respect is that it is not limited or bound to any specific cycle: Emissions are simply measured as the vehicle is driven, be it “off-cycle” or not. This offers a great potential to check, for example, whether emissions outside the regulated range of the RDE test trip window remain within bounds or not.

With a broad statistical sample, it is possible to go far beyond simple averages and determine the on-road emission rates as a function of engine load over the whole range of observed driving conditions. These values can then be directly compared with emission rates from other emission measurements or emission models having an equally fine power disaggregation. Figure 8 compares the on-road NO_x emission rate of diesel Euro 4 cars measured remotely in Zurich (campaigns 2011 to 2014) (Borken-Kleefeld, Franco, & Chen, 2015) with the modeled emission rate from the Swiss (and Austrian, German, Norwegian, and French) standard vehicle emission factor database HBEFA 3.2 (HBEFA 3.2 2014) as a function of engine load. In essence, the emission rate per fuel consumed scales linearly with the engine load for the Euro 4 cars under investigation[10], with approximate a rate of 0.3±0.02 g NO_X/kg per kW/t. Results such as this can be used for independent validation of the emission models and/or to provide actual input data for these models. The on-road emission rates per engine load are also a key input for the conversion to a distance-based emission factor.

---

[10] A linear trend has also been observed for Euro 3 diesel cars, but not any more for Euro 5. With hindsight, we can now ascribe a good part of the non-linear behavior of Euro 5 diesel cars to a defeating control strategy.

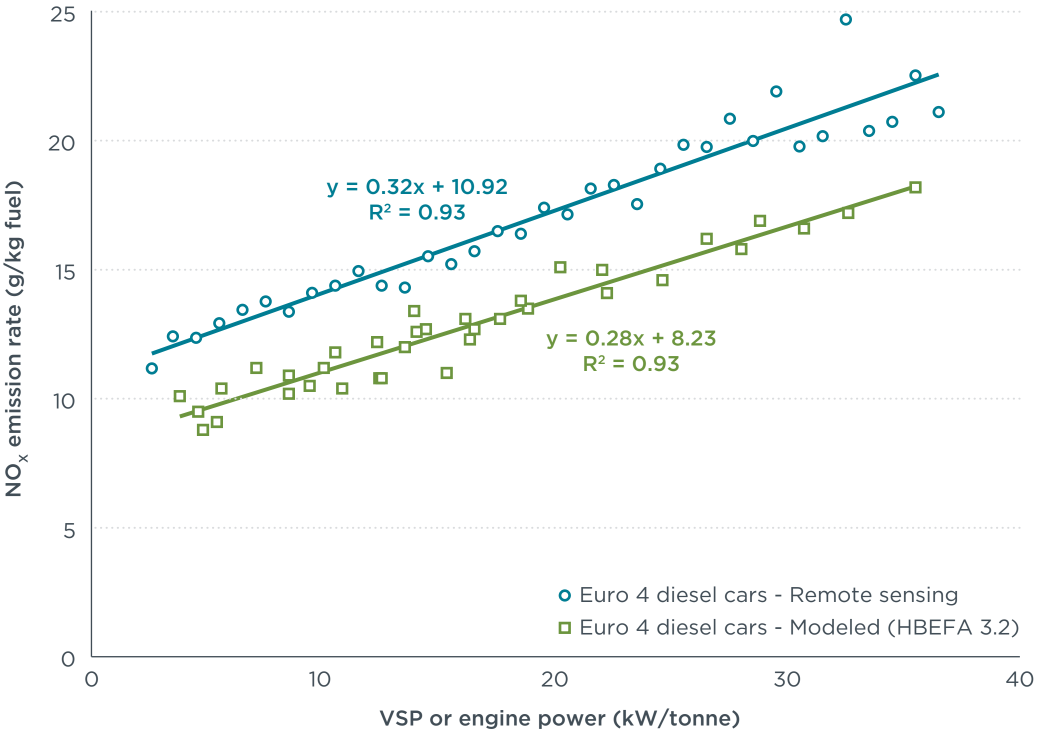

Figure 8: NO_x emission rate as a function of engine power for diesel cars certified to Euro 4 standards: upper line from vehicle remote sensing measurement at Zurich/Gockhausen (Borken-Kleefeld, Franco, & Chen, 2015); red line data from micro-cycles as simulated with HBEFA 3.2.

Data pool from Zurich: 110,000 valid records obtained in four annual campaigns of about 15 days duration each in Gockhausen/Kanton Zurich from 2011 and 2014.

REMOTE SENSING FOR IN-USE SURVEILLANCE OF THE FLEET

How do emission factors vary between vehicle makes and models?

Surveillance of pollutant emissions from the in-use fleet requires a statistically representative sample, which can be offered from remote sensing measurements. With a sufficiently large sample, remote sensing data can be aggregated by vehicle manufacturer (Carslaw & Rhys-Tyler, 2013; Tate, 2015) or even by vehicle model (Borken-Kleefeld, Franco, & Chen, 2015; Pujadas, Domínguez-Sáez, & De la Fuente, 2017). The information on make and model is supplied from the vehicle registry, along with the date of first registration (or the certified emission standard) and further technical details like rated engine power and curb weight, which might be used in even more refined analyses yet to come.

There have been significant differences in the NO_x emission rate of diesel cars between manufacturers throughout the course of the last twenty years: Figure 9 shows the development of average on-road NO_x emissions from Euro 2 to Euro 6 cars by four major manufacturers in Zurich, using data from 2011 to 2014 (Chen & Borken-Kleefeld, 2014; Borken-Kleefeld, Franco, & Chen, 2015).

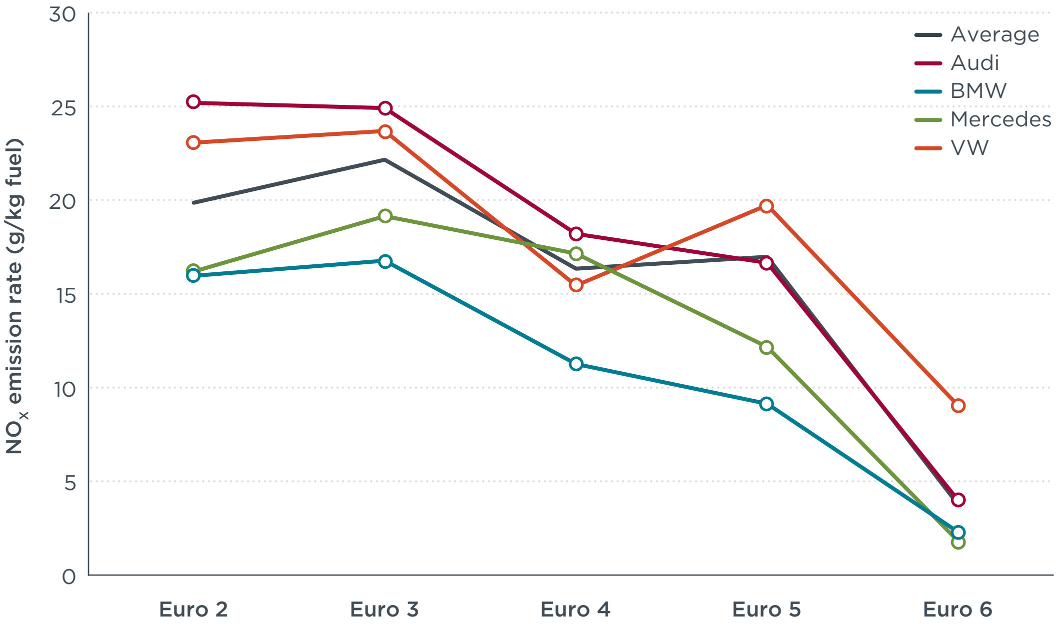

Figure 9: Development of the average NO_x emission rate from different manufacturers from Euro 2 to Euro 6 emission standard. Results from remote sensing campaigns in Zurich 2011 to 2014 (Borken-Kleefeld, Franco, & Chen, 2015).

Data pool from Zurich: 110,000 valid records obtained in four annual campaigns of about 15 days' duration each in Gockhausen/Kanton Zurich from 2011 and 2014.

These on-road emissions are determined without interference or prescription of the driving behavior of the driver nor with vehicle interaction so that defeat strategies are minimal. Sufficient statistics assumed, the ensemble of tests provides a reliable picture of the true on-road emissions. This feature is very desirable for monitoring in-use compliance. It requires a large sample, however, due to factors such as an optimized site selection or through multiple coordinated campaigns.

In the following, we show an example of the extent to which data collected during an actual remote sensing campaign can provide coverage for assessment of emissions from individual vehicle models.

Two related remote sensing campaigns were conducted in fall 2014 and winter 2015 in Madrid. About 200,000 valid vehicle emission records were measured at 28 different sites in the metropolitan area. After filtering for moderate driving conditions (2 to 30 kW/t VSP), about 100,000 records of gasoline and diesel passenger cars remained. The diesel car records from manufacturing year 2005 onwards were grouped by individual car models. As the average car life is about ten years, most diesel cars recorded during these campaigns belong to Euro 4 and Euro 5 norms. For each of these groups, 137 vehicle models have at least five measurement records, more than 80 models have at least 30 repeat measurements, and about 50 different vehicle models have as many as 100 repeat measurements (Table 1).

As the Euro 6 standard became mandatory only in September 2014, there are only 1,400 records (or 3%) with five or more repeat measurements in these campaigns; yet as many as 15 of the most popular models had at least 30 repeat measurements, useful for indicative values. Five models had more than 66 records, and two had more than 100 records. These data indicate any assessment of the very latest models requires either a larger sample size (more measurement days or higher daily traffic rates) or sampling locations where these vehicles make up a larger fraction of the fleet.

Table 1: Number of models with at least five, 30, 66, and 100 RS records from campaigns in 2014 and 2015 in Madrid (Pujadas, Domínguez-Sáez, & De la Fuente, 2017).

Number of vehicle models with at least x measurements	Euro 4 Manuf. years 2005 to 2009	Euro 5 Manuf. years 2010 to 2014	Euro 6 Manuf. years 2014/2015
...Five measurements	137	137	49
...30 measurements	91	81	15
...66 measurements	65	57	5
...100 measurements	52	49	2
Total records with at least five per model	23614	21697	1426
Total records with at least 30 per model	22885	20917	929

So far there have only been few campaigns in Europe with sample sizes bigger than 100,000. To maximize both resources and analytical power, it is therefore highly recommended to pool the data from individual campaigns. Establishing a common remote sensing database is one important aim of the CONOX project.

What is the average deterioration or long-term durability of the emission control system? How do pollutant emissions behave with vehicle age?

Larger sample sizes or repeated remote sensing measurements over the course of a few years allow investigators to track the average emission factor by emission norm over time. This is useful for monitoring vehicle aging and deterioration or, inversely, the long-term durability of emission controls. For this type of analysis measurements are needed of the same vehicle model year (or year of first registration as proxy) at different years and thus at different vehicle ages. Ideally, these data come from the same site or otherwise need to be normalized to the same driving condition. Figure 10 illustrates the increasing NO emission rate from diesel vans/pick-ups equipped with selective catalytic reduction (SCR) systems in the US beginning with vehicle model year 2009. Surprisingly, the NO emission rate increases by 50% and more within just three years of service for model year 2011, 2012, and 2013 vehicles. If the same rapid deterioration takes place in Europe also, then there will be a significant problem with the resulting NO_2 ambient concentrations.

The share of diesel vans/pickups is just 10% in the US light-duty fleet. However, a sample of a few million records recorded annually from routine surveillance in parts of Colorado and Virginia allows the filtering out of even these effects by vehicle model.

Thanks to the large sample sizes, RS provides an excellent means to get representative age-specific emission rates, providing higher-quality data from which to derive deterioration factors.

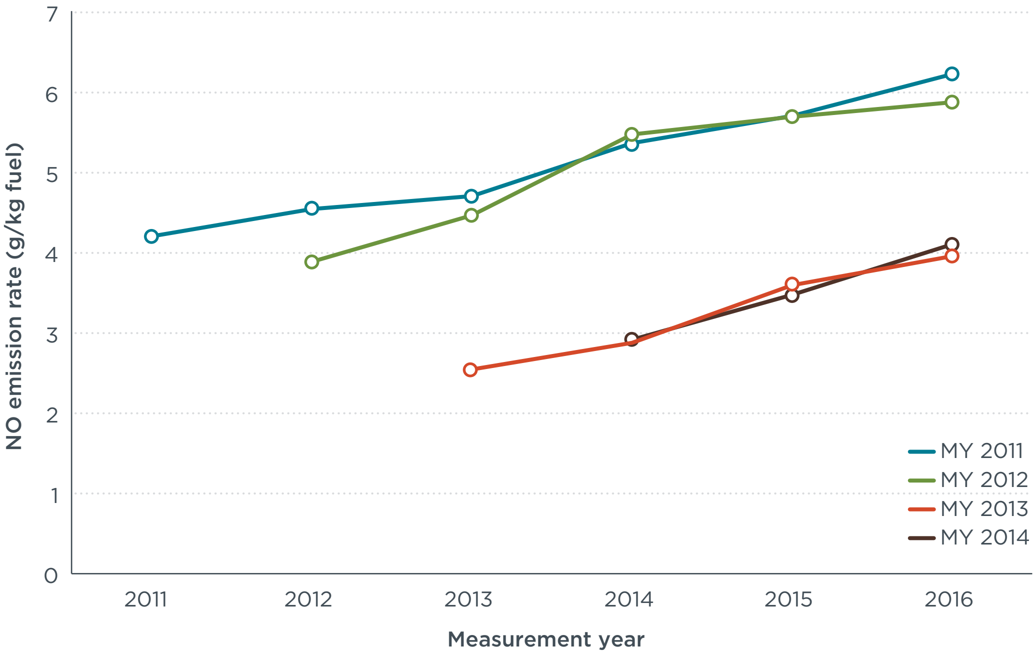

Figure 10: Increase of NO emission rate from SCR-equipped US 3l engine diesel cars for model years 2011 to 2014 (McClintock, 2015; courtesy of OPUS Inspection).

How does the emission factor vary by exhaust after-treatment technology?

If additional information about specific vehicle (aftertreatment) technology is available, the remote sensing records can also be analyzed for the average emission behavior of this technology. One example has already been presented in Figure 10 where the development of SCR after-treatment with vehicle age is followed. Given sufficient data, this can also be refined to the level of individual makes and models, as is the practice now with the comprehensive "clean screen" programs in the US states of Colorado[11] and Virginia[12].

In Europe, pass-by measurements have been made for specific fleets such as taxis (London, (Carslaw & Rhys-Tyler, 2013)) and urban buses (London, Oxford, Gothenburg, Graz (Carslaw & Rhys-Tyler, 2013; Carslaw & Priestman, 2015; Hallquist et al., 2013; De la Fuente, Lopez, & Toudert, 2014); to obtain sufficient statistics they are measured at dedicated lanes or close to their depots (Carslaw & Rhys-Tyler, 2013; Sjödin & Jerksjö, 2008).

How does the emission factor vary by ambient temperature?

Car manufacturers have confirmed that their exhaust after-treatment systems are working optimally only within a certain temperature range (BMVI, 2016). In many cases, this so-called temperature window is narrowly defined between 20°C and 30°C, which is the window set in homologation laboratory testing. Remote sensing data can be taken at various ambient temperatures as they occur during the course of the day. For instance, the most recent measurement campaign in Gothenburg, Sweden, was

---

[11] For information about Colorado's RapidScreen program, see: http://aircarecolorado.com/index.php/rapidscreen/

[12] For information about Virginia's RAPIDPASS program, see: http://www.deq.virginia.gov/Programs/AirCheckVirginia/ForMotoristsVehicleOwners/RAPIDPASSVirginia.aspx

conducted between September and November 2016, with temperatures ranging from about 8°C to 25°C during the day. Analysis of the combined RS measurement data across Europe shows that real-world NO_x emissions increase by 50% for Euro 5 diesel cars as ambient temperatures decrease from 20°C to 10°C (Fig. 11). This reanalysis has already led to a substantial uplift of emission factors included in the Handbook Emission Factors 3.3 (Keller et al., 2017).

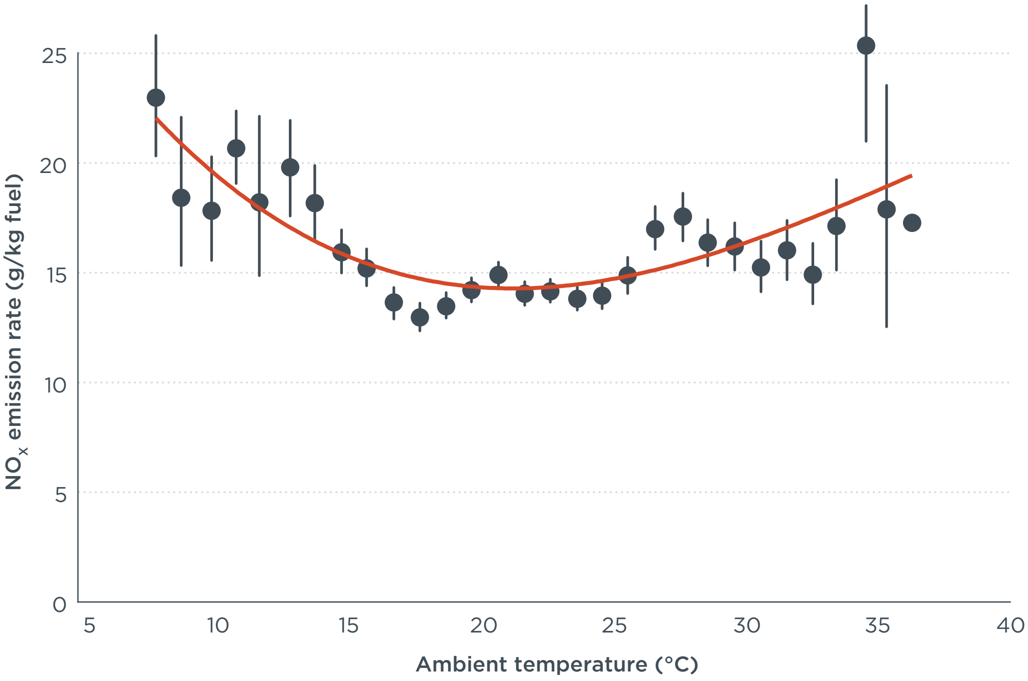

Figure 11: Average NO_x emission rate of Euro 5 diesel cars as a function of ambient temperature. The emission rate is lowest at about 20 °C, but rises then for colder and warmer temperatures[13].

Data pool: 85,000 records of Euro 5 diesel cars from RS measurements in France, Spain, Sweden, Switzerland, and the United Kingdom.

REMOTE SENSING OF INDIVIDUAL VEHICLE FOR INSPECTION & MAINTENANCE

Ascertain clean vehicles and screen out high-emitters

Remote sensing can also be applied to determine the emission performance of individual vehicles. Several US states with air quality problems use pass-by emission measurements to either (1) in the case of excessively high pollutant emissions, notify car drivers that inspection and repair is warranted, or (2) in the case of low emissions, notify car drivers that they are exempted from the next garage-based vehicle inspection test. This kind of test typically requires that the vehicle is measured two or more times under "normal" driving conditions (i.e. within a certain speed and acceleration band).

If the vehicle's emissions under normal driving conditions are repeatedly above some elevated "high-emitter" threshold, the vehicle owner is notified. This notification process does not discriminate with regard to the reason of the excessive emissions. The thresholds are higher for older vehicles and lower for more modern vehicles, certified

---

[13] Analysis by David Carslaw on the CONOX database (09/2017).

initially to more stringent emission limit values. Thus, the high emitter threshold is adapted to the technical progress.

A set-up with two remote sensing devices in a row has been successfully applied in Hong Kong to identify high-emitting light-duty gasoline vehicles and liquid petroleum gas (LPG) fueled taxis. Similarly, remote sensing has been used in a number of Chinese cities as part of high-emitter screening programs. Recently, China's Ministry of Environmental Protection released a remote sensing emission standard for in-use vehicles, which is expected to expand remote sensing programs in Chinese cities (Yang, 2017). Details of the Hong Kong high-emitter screening program are included in the Appendix.

If a certain vehicle make or model, or one specific model year only, has a higher incidence rate for high emitters of one or several pollutants monitored, then this might be an indication of a more systematic technical problem with the engine or the emission control system. The responsible authority thus receives statistically representative data for possible follow-up actions.

Inversely, if a vehicle's emissions under normal driving conditions are repeatedly below some "low-emitter" threshold, the vehicle can be exempted from the next garage based emission inspection. This provides convenience to motorists without any detriment to air quality. This is the essence of a "clean screen" program like that implemented in several US states[14]. Usually, the share of vehicles that can obtain such a remote sensing based clean screen certificate is limited, e.g., up to a maximum of 30% of eligible vehicles[15]. Other car owners must visit a garage for emission inspection. Thus, the performance of the remote sensing emission controls can be monitored independently by local emission tests, and vice versa: the effectiveness of the garage-based tests can be surveyed with on-road remote sensing.

CURRENT DEVELOPMENTS IN EUROPE

Europe's leading remote sensing researchers have established a common data pool from their sampling campaigns (CONOX). Pooling of data greatly enhances the statistical power, scope, and representativeness of the campaigns. The ambition of the collaboration is to determine emission rates per vehicle model, focusing on on-road NOx emissions from diesel cars and vans. The results from this project will demonstrate the suitability of remote sensing for fleet surveillance applications.

In addition, a method has been developed to convert between the remote sensing emission factor unit (gram pollutant per kg fuel) and the unit typically used for regulatory emissions testing (gram pollutant per km driven). This conversion method makes on-road remote sensing measurements directly comparable with chassis dynamometer and PEMS measurements.

Data products from the CONOX collaboration will be fed to instantaneous emission models such as PHEM, and compared with RDE PEMS tests and chassis dynamometer tests. Results will be used to refine, calibrate, and further develop the standard emission factor databases HBEFA and COPERT. The CONOX remote sensing database will be

---

[14] Clean Screen in Virginia: https://rapidpassvirginia.com/VaPublic/.
Clean Screen in Colorado: http://aircarecolorado.com/index.php/rapidscreen/

[15] A car is eligible if it is due to emission inspection within the next 6 months from the date of measurement.

maintained by IVL in Sweden[16]. The intention is for the database to grow continuously as more remote sensing campaigns are conducted.

Methods are also being developed within the pan-European CONOX project to recreate RDE test trip or chassis test cycle results from instantaneous emission rates sourced from remote sensing measurements. These emission rates represent the average emission at a specific engine load, defined by speed and acceleration of the vehicle. When the speed-acceleration profile of the test trip or test cycle is known, the respective time shares can be weighted with the instantaneous emission rates. Their sum should come close to the officially reported result, otherwise a more detailed emission check is warranted.

Many cities across Europe have been facing persistent exceedances of the NO_2 air quality limit value along major roads. Excessive NO_X emissions from diesel cars have contributed to these exceedances. Low emission zones, which exclude cars certified to older emission standards, have not been effective in reducing NO_2 exceedances. There remains uncertainty as to whether Euro 6 cars with RDE tests will eventually fix the problem—and if so, when? Improvements in NO_2 air quality are required sooner rather than later. Therefore, an increasing number of cities are considering a ban of certain or all diesel cars from access to inner parts, for instance: Athens, Hamburg, London, Paris, Stuttgart, Mexico City, and Beijing (Harvey, 2016; Tietge & Diaz, 2017). Some are investigating how much remote sensing can help with informing, monitoring and/or enforcing their measures. The ICCT is supporting these activities with measurements in London and Paris as part of The Real Urban Emissions (TRUE) project (ICCT, 2017).

---

[16] Manager of the CONOX Project: Dr. Åke Sjödin, Air Pollution and Abatement Strategies Unit IVL Swedish Environmental Research Institute. Direct telephone: +46 10 788 67 98. ake.sjodin@ivl.se

THE ROLE OF REMOTE SENSING IN ENHANCED VEHICLE EMISSIONS MONITORING PROGRAMS

To date, the European Union has relied solely on laboratory-based chassis dynamometer testing for regulating pollutant emissions from new light-duty vehicles. With the introduction of RDE test requirements in 2017, the regulation was expanded to include on-road testing using PEMS. In current applications, the scope of these two emission measurement methods—chassis dynamometer and PEMS testing—is similar. Emissions from individual vehicles are measured as the vehicle is operated over a range of conditions delineated either by a laboratory test program or, in the case of RDE testing, by trip specifications and boundary conditions. In the past, the focus on standardized emission testing has meant that manufacturers optimized emission controls (and fuel efficiency measures as well) for the test conditions while disregarding emission reductions in real driving, thus circumventing the goals of emission control legislation.

In many respects, vehicle emission remote sensing is complimentary to both PEMS and chassis dynamometer 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 even 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 tests. The accuracy and representativeness of remote sensing results are essentially determined by the choice of measurement sites, the variation of the vehicles passing, and the total amount of valid emission measurements. The accuracy can be easily increased by larger sample sizes, 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, 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 could supplement existing vehicle emissions test methods to support better real-world control of emissions from motor vehicles.

In the following sections, we consider the use of remote sensing in two complimentary applications. The first—in-use surveillance of vehicle fleets and models—relates to detection of high-emitting vehicle models, where causes of high emissions are the fault of the vehicle manufacturer. These causes include poor design or defects in the emissions control related components; deterioration or poor durability of the emissions control related components; and deliberate cheating or flaunting of the emissions standards, including the use of defeat devices. The second application considers the detection of individual high-emitting vehicles, where causes for high emissions are either the fault of the vehicle owner (e.g., poor vehicle maintenance, removal or tampering of the emission control system), accidental malfunctioning of emission control equipment, or excessive wear. A conceptual diagram showing the potential role of remote sensing in an enhanced European motor vehicle emission control program is presented in Figure 12.

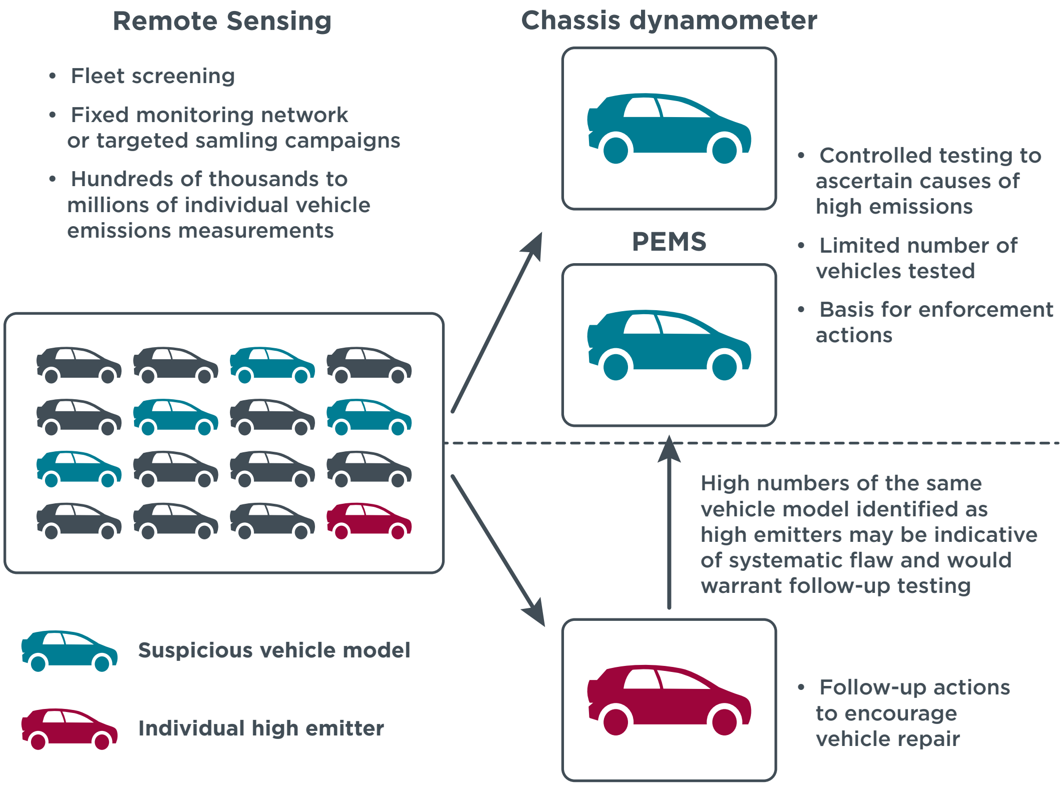

Figure 12: Conceptual diagram showing the potential role of vehicle remote sensing in an enhanced European motor vehicle emission control program.

In-use surveillance of vehicle fleet and models

In-use surveillance of vehicle emissions has been very weak throughout Europe in the past (EP, 2017a). With remote sensing, thousands of vehicles can be scanned in a single day as they pass a single measurement location. This high sampling rate makes vehicle remote sensing very useful as a screening tool for filtering clean and dirty models in actual use. Over the course of a few weeks, tens to hundreds of thousands of instantaneous records can be acquired at well-chosen measurement locations. Together, they form a representative sample of the actual fleet in real driving. The collective data can be broken down by fuel and Euro norm, by age and engine load, or by make and model with statistical significance. This allows profiling of the emission characteristics of makes and models as driven, following their emission development over model generations and production years, down to screening individual vehicles for high emissions.

Likewise, the pass-by measurements of the actual fleet do not entail any preselection of the vehicles. Hence, there is no selection bias by the operators, and vehicles cannot be specifically prepared and provided for the on-road measurement. Instead, the remote sensing emission survey reveals the composition of the fleet. This information comes as an add-on of this measurement technique.

Lastly, the vehicle is measured as driven independent of a prescribed trace and without any instrument attached. Thus, there can be no bias introduced by a skilled test driver, nor can cycle detection be applied to tune the emission after treatment system specifically for the measurement situation.

Europe currently lacks a legal framework that would give in-use remote sensing measurements weight and relevance. In the context of proposed changes to the European type-approval and market surveillance framework, vehicle emission remote sensing could be incorporated as an additional source of information on the emissions performance of the in-use fleet. Remote sensing data collected either in targeted sampling campaigns or through the establishment of a fixed monitoring network would provide valuable emissions information to authorities and would help in the identification of vehicle models with poor or suspicious real-world performance[17].

The use of remote sensing data would support a more efficient application of the more rigorous, and costly, measurement methods such as PEMS and chassis dynamometer testing as part of in-use surveillance programs. Thus, remote sensing appears complementary to existing techniques; due to the very large sample sizes, remote sensing can be used to screen the emissions performance of the fleet. Detailed tests of single vehicles might then be used for follow-up compliance testing.

Individual high-emitter screening

Vehicle emission remote sensing can be also applied to filter out individual high-emitting vehicles. This usually requires that the same vehicle is measured with a suspiciously high emission rate multiple times within a short time span and under normal driving conditions. The emission rates of CO, HC, and NO_x are not necessarily correlated with each other; therefore, all components need to be screened for possible high emissions. High-emitter screening programs utilizing vehicle remote sensing have been successfully implemented in other regions as part of inspection and maintenance programs or as stand-alone in-use emission control programs, rigorously for instance in Hong Kong (see Appendix). In both cases, programs are designed to identify individual vehicles that have emissions significantly greater than expected, whether due to poor maintenance or intentional removal or tampering with emission control equipment. These high-emitting vehicles contribute disproportionately to emissions inventories, making them a good target for in-use emissions control programs. A high number of vehicles of the same model identified as high emitters may be indicative of a systematic flaw in the emissions control system, rather than poor maintenance, and would warrant follow-up testing.

---

[17] As remote sensing yields instantaneous emission rates for known operating conditions, these data can be used to generate cycle emissions: The speed and acceleration phases of the test cycle or trip under consideration are sourced by the instantaneous emission rates as measured on the road by remote sensing. If differences to the official tests are too high, further detailed testing will be warranted.

REFERENCES

Andre, M., Hammarstrom, U. & Reynaud, I. (1999). Driving Statistics for the Assessment of Pollutant Emissions from Road Transport. LTE 9906. Bron/FR: INRETS.

Anenberg, S.C., Miller, J., Minjares, R., Du, L., Henze, D.K., Lacey, F., Malley, C.S., et al. (2017). Impacts and Mitigation of Excess Diesel-Related NO_X Emissions in 11 Major Vehicle Markets. *Nature*, May. doi:10.1038/nature22086.

Bishop, G. A., Starkey, J.R., Ihlenfeldt, A., Williams, W.J., & Stedman, D.H. (1989). IR Long-Path Photometry: A Remote Sensing Tool for Automobile Emissions. *Analytical Chemistry* 61 (10): 671 A-677 A.

Bishop, G. A., & Stedman, D.H. (2008). A Decade of On-Road Emissions Measurements. *Environmental Science & Technology* 42 (5): 1651–56. doi:10.1021/es702413b.

Bishop, G.A., Schuchmann, B.G., Stedman, D.H., & Lawson, D.R. (2012). Multispecies Remote Sensing Measurements of Vehicle Emissions on Sherman Way in Van Nuys, California. *Journal of the Air & Waste Management Association* 62 (10): 1127–33. doi:10.1080/10962247.2012.699015.

BMVI. (2016). Bericht Der Untersuchungskommission Volkswagen—Untersuchungen Und Verwaltungsrechtliche Maßnahmen Zu Volkswagen, Ergebnisse Der Felduntersuchung Des Kraftfahrt-Bundesamtes Zu Unzulässigen Abschalteinrichtungen Bei Dieselfahrzeugen Und Schlussfolgerungen. Berlin, Germany: Bundesministerium für Verkehr und digitale Infrastruktur.

Baldino, C., Tietge, U., Muncrief, R., Bernard, Y. & Mock. P. (2017). *Road tested: Comparative overview of real-world vs. type-approval* NO_X *and* CO_2 *emissions from diesel cars in Europe.* International Council on Clean Transportation. Retrieved from http://www.theicct.org/publications/road-tested-comparative-overview-real-world-versus-type-approval-nox-and-co2-emissions

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

Borken-Kleefeld, J., Franco, V., & Chen, Y. (2015). *Weitere Auswertungen Der Remote Sensing Messungen Des AWEL Zürich*. Final Report for AWEL Zurich. Vienna.

Borken-Kleefeld, J. & Chen, Y. (2015). New Emission Deterioration Rates for Gasoline Cars – Results from Long-Term Measurements." *Atmospheric Environment* 101 (January): 58–64. doi:10.1016/j.atmosenv.2014.11.013.

Burgard, Daniel A., Gary A. Bishop, Donald H. Stedman, Viktoria H. Gessner, and Christian Daeschlein. (2006). Remote Sensing of In-Use Heavy-Duty Diesel Trucks. *Environmental Science & Technology* 40 (22): 6938–42. doi:10.1021/es060989a.

Carslaw, D. (2014). Recent Findings from Comprehensive Vehicle Emission Remote Sensing Measurements. London, June 23.

Carslaw, D., & Priestman. M. (2015). *Analysis of the 2013 Vehicle Emission Remote Sensing Campaigns Data.* London: King's College. Retrieved from https://uk-air.defra.gov.uk/assets/documents/reports/cat15/1511251131_Analysis_of_the_2013_vehicle_emission_remote_sensing_campaigns_data.pdf.

Carslaw, D., & Rhys-Tyler, G.A. (2013). *Remote Sensing of NO_2 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. file:///C:/HOME/IIASA/HighEmitters/Lit/DefraRemoteSensingReport_2013.pdf.

Carslaw, D.C., Beevers, S.D., Tate, J.E., Westmoreland, E.J., & Williams, M.L. (2011). Recent Evidence Concerning Higher NOx Emissions from Passenger Cars and Light Duty Vehicles. *Atmospheric Environment* 45 (39): 7053–63. doi:10.1016/j.atmosenv.2011.09.063.

Carslaw, D.C., Murrells, T.P., Andersson, J., & Keenan, M. (2016). Have Vehicle Emissions of Primary NO2 Peaked? *Faraday Discuss.* 189: 439–54. doi:10.1039/C5FD00162E.

Carslaw, D.C., & Rhys-Tyler, G. (2013). New Insights from Comprehensive On-Road Measurements of NOx, NO2 and NH3 from Vehicle Emission Remote Sensing in London, UK. *Atmospheric Environment* 81 (December): 339–47. doi:10.1016/j.atmosenv.2013.09.026.

Carslaw, D.C., Williams, M.L., Tate, J.E., & Beevers, S.D. (2013). The Importance of High Vehicle Power for Passenger Car Emissions. *Atmospheric Environment* 68 (April): 8–16. doi:10.1016/j.atmosenv.2012.11.033.

Chen, Y., & Borken-Kleefeld, J. (2016). NOx Emissions from Diesel Passenger Cars Worsen with Age. *Environmental Science & Technology* 50 (7): 3327–3332. doi:10.1021/acs.est.5b04704.

Chen, Y., & Borken-Kleefeld, J. (2014). Real-Driving Emissions from Cars and Light Commercial Vehicles – Results from 13 Years Remote Sensing at Zurich/CH. *Atmospheric Environment* 88 (May): 157–64. doi:10.1016/j.atmosenv.2014.01.040.

De la Fuente, J., Lopez, M., & Toudert, J. (2014). Real Emissions from the City and Public Bus Fleets in Graz. Graz, Austria.

DeFries, T. (2016). Evaluation of EDAR for Measurement of Simulated Exhaust Emissions.

Ekström, M., Sjödin, Å., & Andreasson, K. (2004). Evaluation of the COPERT III Emission Model with On-Road Optical Remote Sensing Measurements. *Atmospheric Environment* 38 (38): 6631–41. doi:10.1016/j.atmosenv.2004.07.019.

European Parliament (EP). (2017a). Report on the Inquiry into Emission Measurements in the Automotive Sector (2016/2215(INI)). Final Report A8–0049/2017. Brussels: European Parliament, Committee of Inquiry into Emission Measurements in the Automotive Sector.

European Parliament (EP). (2017b). *Inquiry into emission measurements in the automotive sector. European Parliament recommendation of 4 April 2017 to the Council and the Commission following the inquiry into emission measurements in the automotive sector (2016/2908(RSP)).* Retrieved from http://www.europarl.europa.eu/sides/getDoc.do?type=TA&reference=P8-TA-2017-0100&language=EN&ring=B8-2017-0177

Goetsch, M. 2013. *Bericht Und Auswertung RSD Messungen 2012*. Zurich: Amt für Abfall, Wasser, Energie und Luft, Lufthygiene, Baudirektion Kanton Zurich. http://www.ji.zh.ch/content/dam/baudirektion/awel/luft_asbest_elektrosmog/verkehr/rsd/dokumente/RSD_Bericht_2012.pdf.

Goetsch, M., Alt, G.-M., Delb, V., & Sintermann, J. (2017). *RSD Messungen 2016: Auswertung Und Bericht.* Zurich: Amt für Abfall, Wasser, Energie und Luft, Abteilung Luft, Baudirektion Kanton Zurich. Retrieved from http://www.awel.zh.ch/content/dam/baudirektion/awel/luft_asbest_elektrosmog/verkehr/rsd/dokumente/RSD_Bericht_2016.pdf.

Hager Environmental. (n.d). Hager Environmental & Atmospheric Technologies, LLC—Information Package. Knoxville, TN.

Hager, J. S. & Yerem, G. (2014). *U.S. Patent No. 8,654,335 B2*. Washington, DC: U.S. Patent and Trademark Office.

Hallquist, Å.M., Jerksjö, M., Fallgren, H., Westerlund, J., & Sjödin, Å. (2013). Particle and Gaseous Emissions from Individual Diesel and CNG Buses. *Atmospheric Chemistry and Physics* 13 (10): 5337–50. doi:10.5194/acp-13-5337-2013.

Harvey, F. (2016, December 2). Four of World's Biggest Cities to Ban Diesel Cars from Their Centres. *The Guardian*. Retrieved from https://www.theguardian.com/environment/2016/dec/02/four-of-worlds-biggest-cities-to-ban-diesel-cars-from-their-centres. HBEFA 3.2. (2014, July). HBEFA—Handbook Emission Factors for Road Transport. http://www.hbefa.net/d/index.html.

International Council on Clean Transportation (ICCT). (2017). *Identifying clean vehicles to improve air quality in Paris and London*. Retrieved from http://www.theicct.org/news/paris-london-clean-vehicles-press-stmnt-march2016

International Council on Clean Transportation (ICCT). (2013). Guidance Note about On-Road Vehicle Emissions Remote Sensing. San Francisco: ICCT. Retrieved from http://theicct.org/road-vehicle-emissions-remote-sensing.

Jimenez-Palacios, J.L. (1998). Understanding and Quantifying Motor Vehicle Emissions with Vehicle Specific Power and TILDAS Remote Sensing. PhD Thesis, Cambridge, MA: Massachusetts Institute of Technology. Retrieved from http://zanran_storage.s3.amazonaws.com/cires.colorado.edu/ContentPages/81873500.pdf.

Jonson, J. E., Borken-Kleefeld, J., Simpson, D., Nyiri, A., Posch, M., & Heyes, C. (2017). Impact of Excess NOx Emissions from Diesel Cars on Air Quality, Public Health and Eutrophication in Europe. *Environ. Res. Lett.*, September.

Keller, M., Hausberger, S., Matzer, C., Wuethrich, P., & Notter, B. (2017). HBEFA Version 3.3—Background Documentation. Bern, Switzerland.

Kishan, S. (2017). Evaluation of the Heat's On-Road Infrared Laser RSD For Exhaust Emissions Measure. Presented at the 7th International PEMS Conference, Riverside, CA, March 31.

Kühlwein, J., Rexeis, M., Luz, R., & Hausberger, S. (2013). Update of Emission Factors for EURO 5 and EURO 6 Passenger Cars for the HBEFA Version 3.2. Final Report I-25/2013/ Rex EM-I 2011/20 679. Graz, Austria: IVK, TU Graz.

Mazzoleni, C., Moosmüller, H., Kuhns, H.D., Keislar, R.E., Barber, P.W., Nikolic, D., Nussbaum, N.J., & Watson, J.G. (2004). Correlation between Automotive CO, HC, NO, and PM Emission Factors from on-Road Remote Sensing: Implications for Inspection and Maintenance Programs. *Transportation Research Part D: Transport and Environment* 9 (6): 477–496.

McClintock, P. (2012). The Colorado Remote Sensing Program January–December 2011. Prepared for the Colorado Department of Public Health and Environment. Marina Del Rey, CA. Envirotest Systems Inc.

McClintock, P. (2015). High NO_x Emissions from Light Diesel Vehicles Also Observed on US Roads. Long Beach, CA, March 22.

Mock, P., & German, J. (2015). *The future of vehicle emissions testing and compliance*. International Council on Clean transportation. Retrieved from http://www.theicct.org/future-of-vehicle-testing

Mock, P. (2017). *Real-Driving Emissions test procedure for exhaust gas pollutant emissions of cars and light commercial vehicles in Europe*. International Council on Clean Transportation. Retrieved from http://www.theicct.org/RDE-test-procedure-exhaust-gas-pollutant-emissions-cars-and-LCVs

Muncrief, R. (2016). *NO_x emissions from heavy-duty and light-duty diesel vehicles in the EU: Comparison of real-world performance and current type-approval requirements*. International Council on Clean Transportation. Retrieved from http://www.theicct.org/nox-europe-hdv-ldv-comparison-jan2017

Pujadas, M., Domínguez-Sáez, A., & De la Fuente, J. (2017). Real-Driving Emissions of Circulating Spanish Car Fleet in 2015 Using RSD Technology. *Science of The Total Environment* 576 (January): 193–209. doi:10.1016/j.scitotenv.2016.10.049.

Rhys-Tyler, G.A., and Bell, M.C. (2012). Toward Reconciling Instantaneous Roadside Measurements of Light Duty Vehicle Exhaust Emissions with Type Approval Driving Cycles. *Environmental Science & Technology* 46 (19): 10532–38. doi:10.1021/es3006817.

Ropkins, K. (2017). Some Observations Based on Complementary International Evaluations of Edar Vehicle Emissions Remote Sensing Technology Sensing. Presented at the 7th International PEMS Conference, Riverside, CA, March 31. Retrieved from http://www.cert.ucr.edu/events/pems/presentations/KRopkins_EDAR_PEMSPaper2017_v2.pdf.

Ropkins, K., DeFries, T.H., Pope, F., Green, D.C., Kemper, J., Kishan, S., Fuller, G.W., et al. (2017). Evaluation of EDAR Vehicle Emissions Remote Sensing Technology. *Science of The Total Environment* 609 (December): 1464–74. doi:10.1016/j.scitotenv.2017.07.137.

Rushton, C.E., Tate, J.E., Shepherd, S.P., &Carslaw, D.C. (2017, March). 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 & Waste Management Association*. doi:10.1080/10962247.2017.1296504.

Sjödin, \AA., and Jerksjö, M. (2008). Evaluation of European Road Transport Emission Models against On-Road Emission Data as Measured by Optical Remote Sensing. In *17th International Transport and Air Pollution Conference*.

Tate, J. (2015). Real Driving Emissions (RDE): Results from the 2015 Remote Sensing Campaigns (UK). Presented at the Routes to Clean Air Conference, IAQM, Bristol, UK, October 23.

Tietge, U. & Díaz, S. (2017). *Cities driving diesel out of the European car market*. International Council on Clean Transportation. Retrieved from http://theicct.org/blogs/staff/cities-driving-diesel-out-european-car-market

US EPA. (1996). User Guide and Description For Interim Remote Sensing Program Credit Utility. EPA/AA/AMD/EIG/96-01. Ann Arbor, MI: Certification and Compliance Division Office of Transportation and Air Quality.

US EPA. (1998). Description and Documentation for Interim Vehicle Clean Screening Credit Utility. EPA420-P-98-008. Ann Arbor, MI: Certification and Compliance Division Office of Transportation and Air Quality.

US EPA. (2002). Guidance on Use of Remote Sensing for Evaluation of I/M Program Performance. EPA420-B-02-001. Ann Arbor, MI: Certification and Compliance Division Office of Transportation and Air Quality.

Van Zyl, P.S., Ligterink, N., Kadijk, G., Borken-Kleefeld, J., & Y. Chen, Y. (2015). *In-Use Compliance and Deterioration of Vehicle Emissions*. TNO2015 R11043. Delft, Netherlands: TNO. Retrieved from 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

Yang, Z. (2017). *Remote-sensing regulation for measuring exhaust pollutants from in-use diesel vehicles in China*. International Council on Clean Transportation. Retrieved from http://www.theicct.org/China-diesel-remote-sensing-regulation

Yanowitz, J., McCormick, R.L., & Graboski, M.S. (2000). In-Use Emissions from Heavy-Duty Diesel Vehicles. *Environmental Science & Technology* 34 (5): 729–40. doi:10.1021/es990903w.

Zhang, Y., Bishop, G.A., & Stedman, D.H. (1994). Automobile Emissions Are Statistically Gamma Distributed. *Environmental Science & Technology* 28 (7): 1370–1374.

APPENDIX

OVERVIEW OF REMOTE SENSING CAMPAIGNS IN EUROPE SINCE 1991

On-road vehicle exhaust emission measurements by remote sensing have been performed in Europe since 1991. The list below shows the long history of its introduction in Europe and the diverse applications of the different measurement campaigns. However, it is also apparent that most measurement campaigns have been small in scale and the number of valid records remains limited. In consequence, the full analytical potential offered by on-road emission measurement has never been exploited as statistics from most campaigns have been too limited for an analysis of emission rates by manufacturer and vehicle model. The analytical power will therefore be greatly expanded as the groups listed below have started pooling their measurement data. In 2017 several bigger campaigns are being conducted, among others in Spain, London and Zurich. They are expected to add another 300,000 to 400,000 up-to-date records.

Sweden

Sweden 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.
- Raise driver awareness and increase 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 NO_2 emissions from light-duty diesel vehicles in real-world driving.
- Monitor emission levels 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 and 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 and 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.
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, France, May 24-26, 240-254.

Switzerland

The longest time series of remote sensing measurements in Europe, if not worldwide, has been recorded at the outskirts of Zurich. 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[18,19]. Key advantages of these measurements include:

- They 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

---

[18] (Goetsch 2013)
[19] (Goetsch et al. 2017)

their high on-road NO/NO_X 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 NO_X emission rate of diesel cars has even increased for over a decade[20].

- The data set is rich enough to be differentiated by model year and emission standard; the long time series has allowed for deriving new deterioration rates for gasoline[21] and diesel cars[22].
- 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[23], COPERT, and VERSIT[24], to compare emissions by vehicle brand and model, searching for high emitters[25], among others.

Location	Years	# records	Site characteristics	Ref.
Zurich/Switzerland	Since 2000 annually during 8-12 weeks. Last campaign 2016.	~500,000	Extra-urban, 9% uphill gradient	AWEL various years; EMPA 2003, 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 suburban London have been intensely measured in repeated campaigns, with particular emphasis to determine NO and primary NO_2 emissions from diesel cars, from taxis and buses[26]. Efforts have been made to analyze the impact of specific after-treatment technology and/or vehicle manufacturers on the resulting emissions, notably for taxis and buses. Results have been published widely and serve as input to ongoing efforts to reduce London's PM and NO_2 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 vehicles have been measured in Aberdeen, Leeds, Oxford, Cambridge, York, Sowerby, Halifax, and other cities since 2009 (mostly by James Tate

---

[20] Chen and Borken-Kleefeld, 2014b.

[21] Borken-Kleefeld and Chen, 2015.

[22] Chen and Borken-Kleefeld, 2016.

[23] Kühlwein et al., 2013; Keller et al., 2017.

[24] Van Zyl et al., 2015.

[25] Borken-Kleefeld, 2012.

[26] Carslaw et al., 2011; Carslaw and Rhys-Tyler, 2013; Carslaw and Priestman, 2015; Carslaw et al. 2016; Carslaw and Rhys-Tyler, 2013.

from ITS Leeds[27]). Again, these measurements at various places gave rise to a number of research and policy possibilities, including:

- They characterize 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 can be 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 that can calculate very localized emissions, e.g., at traffic intersections and individual streets.

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 NO_2 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, November 28). Vehicle Emission Measurement and Analysis - Cambridge City Council. Draft Project Report. University of Leeds, Institute for Transport Studies.
Tate, J. (2013, December 3). Vehicle Emission Measurement and Analysis – Sheffield City Council. Final Project Report. University of Leeds, Institute for Transport Studies.
Tate, J. (2016, April 7). Vehicle Emission Measurement and Analysis - Aberdeen City Council. Final Project Report. University of Leeds, Institute for Transport Studies.
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.

---

[27] (D. C. Carslaw et al. 2011, 2013)

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 NO_x 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[28]. The Spanish Ministry of Environment proposed a draft Royal Decree[29] 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 and surroundings 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 the Middle East (Teheran) and Africa (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 on taxis 1 site in port focusing on trucks	Technet & AJ NN2010
Granollers / ES	2011	10,000	2 urban sites	Technet 2012
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, April 15). 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.
Technet & Ajuntament de Valencia. (2008, September 15). 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.
Technet & Junta de Andalucia. (2009, March 31). 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.
Technet & Ajuntament de NN. (2010, April). Estudio de caracterización del tráfico rodado en materia de emisiones en la ciudad de NN. NN/Madrid.
Technet & Ayuntamento Granollers. (2012, March). Caracterización de las Emisiones del Tráfico en Granollers. Madrid. Retrieved from http://www.granollers.cat/sites/default/files/antigues_d6/pagina/2012/06/20120531_Resumen%20Ejecutivo_FG.pdf
Pujadas, M., Domínguez-Sáez, A., & De la Fuente, J. (2017). Real-Driving Emissions of Circulating Spanish Car Fleet in 2015 Using RSD Technology. Science of The Total Environment 576 (January): 193–209.

---

[28] https://rslab-es.jimdo.com/iso-17025/

[29] http://www.mapama.gob.es/es/calidad-y-evaluacion-ambiental/participacion-publica/PP_2013_Proyecto_RD_emisiones_vehiculos.aspx#

HIGH-EMITTER SCREENING IN HONG KONG/CHINA[30]

In September, 2014, Hong Kong implemented a remote sensing screening program to identify high-emitting light-duty gasoline vehicles and taxis fueled by liquid petroleum gas (LPG). The program utilizes two remote sensing instruments set up in a series, approximately 10-15 meters apart. The instruments are rotated among 100 sampling sites throughout the city to provide greater coverage of the in-use vehicle fleet. Both remote sensing instruments monitor CO, HC, and NO_x emissions from passing vehicles. Results from remote sensing measurements are compared against predetermined cut points that apply to vehicles meeting different emission standards. If a vehicle is measured by both remote sensing instruments to have emissions above the applicable cut point, an Emission Testing Notice (ETN) is sent to the vehicle's owner. After receiving the ETN, the owner is required to bring the vehicle to an emission testing centre within 12 business days, where emissions are measured using a chassis dynamometer. If the emissions defects have not been repaired, the vehicle license can be canceled.

Between 2014 and 2016, approximately 1.3 million remote sensing measurement records representing 311,000 unique vehicles were collected through the Hong Kong high-emitter screening program[31]. This sample encompasses 30% of the private car fleet and 100% of the taxi fleet in Hong Kong. During this time period, 7,236 ETNs were issued to vehicles measured to have emissions in excess of remote sensing emission cut point levels. Approximately 20% of the LPG taxi fleet were cited as high emitters through this program. The overall remote sensing failure rate was approximately 2%.

---

[30] There are several US states that have been running a high-emitter detection program. The results have been reported e.g. in Section 1.4.3 of this Guidance Document: http://www.theicct.org/road-vehicle-emissions-remote-sensing. The Hong Kong application is referenced here as an application outside the United States with very tangible results.

[31] Personal communication, YS Yam, Hong Kong Environmental Protection Department.