European Commission

JRC TECHNICAL REPORTS

Potential of Remote Sensing Devices (RSDs) to screen vehicle emissions

Assessment of RSD measurement performance

C. Gruening, P. Bonnel, M. Clairotte,
B. Giechaskiel, V. Valverde, A. Zardini,
M. Carriero

2019

Joint Research Centre

EUR 29871 EN

Contact information

Name: Carsten Gruening
Address: European Commission, Joint Research Centre, via E. Fermi 2749, I-21027 Ispra (VA), Italy
Email: carsten.gruening@ec.europa.eu

EU Science Hub

https://ec.europa.eu/jrc

JRC117894

EUR 29871 EN

PDF	ISBN 978-92-76-11820-6	ISSN 1831-9424	doi:10.2760/277092
Print	ISBN 978-92-76-11819-0	ISSN 1018-5593	doi:10.2760/25928

Luxembourg: Publications Office of the European Union, 2019

How to cite this report: C. Gruening, P. Bonnel, M. Clairotte, B. Giechaskiel, V. Valverde, A. Zardini, and M. Carriero, *Potential of Remote Sensing Devices (RSDs) to screen vehicle emissions - Assessment of RSD measurement performance*, EUR 29871 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-79-11820-6, doi:10.2760/277092, JRC117894.

Contents

Acknowledgements

The authors gratefully acknowledge the support of the two companies HEAT and OPUS RSE in performing the assessment exercise for the RSD measurements and their constructive contribution to improve the final version of this report. The authors would also like to thank all the JRC's Sustainable Transport Unit's personnel that contributed to the experimental work back in 2017, the colleagues from the Air and Climate Unit for the ambient air data and last but not least the Ispra site security team for securing the road traffic during the experimental work.

Authors

C. Gruening, M. Clairotte, P. Bonnel, B. Giechaskiel, V. Valverde, A. Zardini, M. Carriero

Abstract

This report on the potential of Remote Sensing Devices (RSDs) to screen vehicle emissions summarizes the findings of a one-week measurement campaign performed in July 2017.

Two remote sensing devices from the companies HEAT and OPUS were installed on the roadside at the JRC Ispra site. Reference vehicles equipped with Portable Emission Measurement System (PEMS) were driven by the instruments serving as reference measurement systems to compare their results to the RSDs for different emissions. The focus during this exercise was on the gaseous pollutants NO, NO_2 and CO from light duty vehicles. RSD and PEMS based measurements showed good agreement of the observed pollutants to CO_2 ratios, the basic observable of RSDs, within the instruments range of observation.

Challenged with a larger set of different vehicles, the RSD measurements provided an overview of expected observations for different vehicle types and emission standards.

The RSD performance has been put in relation to emissions that are expected from latest EURO 6 compliant vehicles on the road using instantaneous pollution to CO_2 ratios from recent Real Driving Emissions (RDE) tests. Distinguishable probability distributions for NO-to-CO_2 ratios for different emission standards and single vehicles were obtained.

These findings indicate that Remote Sensing Devices constitute a promising technology for the screening of vehicle emissions in order to identify high or low polluting vehicles and vehicle types under specific driving conditions.

1 Introduction

The European Commission has introduced measures to address the verification of emissions performance of vehicles, in particular for the Euro 6 standards, through market surveillance tasks [1] and in-service conformity checks [2]. The complementary responsibilities have been attributed to the automotive industry, the European Union (EU) National Authorities and the Commission for the verification of the vehicle and engines emissions compliance. For light-duty vehicles, this includes for instance testing both on the Type 1 cycle (Worldwide Harmonised Light Vehicle Test Procedure (WLTP), conducted on a vehicle chassis dynamometer) and the Type 1a (RDE, conducted on road using Portable Emission Measurement Systems [PEMS]).

One of the "upstream" tasks should be to perform a proper risk assessment in order to ensure an unbiased and efficient selection of the vehicles to be tested by the responsible authorities for the market surveillance and in-service conformity activities. For instance, it should be ensured that the highest emitters within a given category (e.g. emissions standard) are appropriately tested and checked for potential problems (e.g. ageing, tampering by the vehicle owner or illegal emissions strategies by the car manufacturer).

To support the market surveillance vehicle selection process, the European Commission started to assess the fitness-for-purpose of Remote Sensing Devices (RSDs). In support to this activity, the JRC has set up an evaluation program, designed to assess the measurement performance of commercially available Remote Sensing systems under real-world conditions, i.e. verifying the equipment measurements aside the road, under real conditions of use. The market for such equipment is limited but well known from the deployed instrumentation and the past programs conducted e.g. in the United States, Switzerland, Spain, United Kingdom and Hong-Kong [[3], [4], [5]–[7], [8], [9], [10]]. The identified commercially available RSDs fulfilled the following minimum requirements:

• To be easily installed along the road and be capable to operate during several hours of unattended operation with a constant measurement quality;

• To measure vehicle speed and remotely the mass of some of the regulated pollutants (e.g. NO_x, CO_2, CO, THC, particles) in the vehicle exhaust;

• Using the vehicle number plate, to have the ability to retrieve the vehicle technical characteristics from a local registration database.

In addition to the above basic requirements, the RSD specifications and measurement procedures were established according to the US-EPA guidance on Use of Remote Sensing for Evaluation ([11]). Data were collected in July 2017 during one week on the JRC Ispra site. The two RSDs were confronted with a fleet of known vehicles of various technologies and emissions standards.

A few vehicles were equipped with PEMS to compare the RSD measurements with the actual tailpipe emissions at the location of the RSDs.

2 Remote Sensing Equipment - Technical features and operation

2.1 RSD Operation

2.1.1 General

The schematics of the RSD on-road installation in Figure 1 shows a typical installation of such a system to check the pollutants in the exhaust of vehicles equipped with internal combustion engines. A typical RSD measures CO, CO_2, NO, NO_2 and - depending on the measurement technique used - physical properties of the particulate matter emissions.

When the vehicle passes through the measurement system, the RSD analyses the exhaust plume based on optical absorption spectroscopy. Because the effective plume path length and amount of plume seen depend on turbulences, wind speed and other factors, the RSDs determine directly ratios of pollutants to CO_2. The underlying theories and measurement principles are detailed and reviewed in the relevant literature, ([12], [13], [14]), a recent usage survey of Remote Sensing worldwide is presented in [15].

At the same time, the RSD provides the vehicle speed, acceleration and a video system takes a picture of the license plate. The video provides the possibility to later retrieve the vehicle technical characteristics from a registration database, when available.

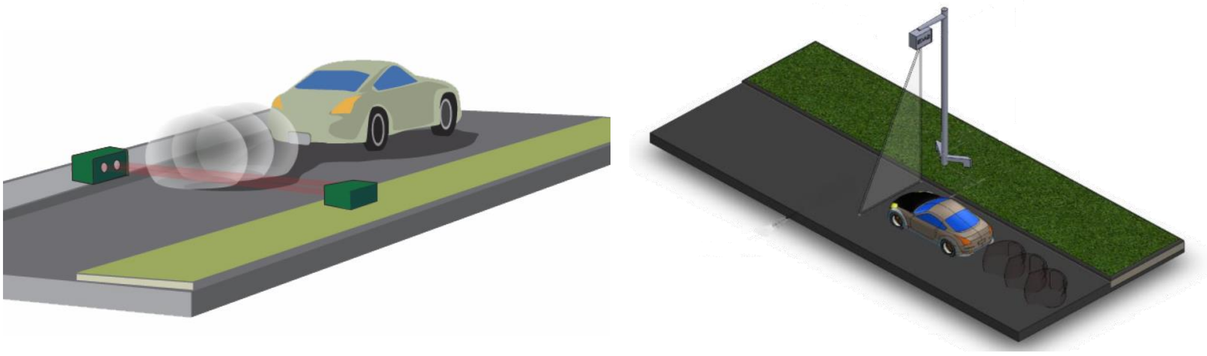


Figure 1. Schematics of the RSD on-road installation; left OPUS (horizontal setup with light emitter and detector unit plus reflector), right EDAR (with downward looking unit, reflector strip installed on the road).

A brief overview of the systems' specific features that are deemed relevant for this report is given in the following paragraph. The details were provided by the manufacturers and do not imply an endorsement by the JRC. For further details, the reader is referred to the manufacturers' product descriptions and reviews.

2.1.2 Specific features of the tested Remote Sensing systems

HEAT:

This section briefly describes the main features of the EDAR system (Emission Detection And Reporting) from HEAT (Hager Environmental & Atmospheric Technologies), further details can be found elsewhere ([16], www.heatremotesensing.com).

EDAR is based on Differential Absorption LiDAR (Light Detection and Ranging) Spectroscopy and capable of remotely detecting and measuring the infrared absorption of pollutants emitted by in-use vehicles. EDAR emits a sheet of infrared laser light in a top down orientation from above the road and measures the exhaust plume as the vehicle passes underneath. The system is comprised of an eye-safe laser-based infrared gas sensor system including a retro-reflector that is placed on the road surface, a vehicle speed/acceleration sensor, and a license plate reader. It is placed on a single pole that is deployable roadside in either a temporary or permanent installation. EDAR records automatically vehicle emissions of the pollutants CO, CO_2, NO, NO_2, hydrocarbons (HC) and Particulate Matter (PM).

Figure 2 shows an example of the report that is produced by EDAR for every vehicle detected and evaluated. As displayed, EDAR takes a 2D image of the vehicle, its emission plume as well as the ancillary parameters, a pass or fail indication for internal QA/QC procedures, and an actual image of the vehicle itself. All data are combined for further data processing and analysis. Processing of EDAR data in the scope of this report has been done by HEAT.

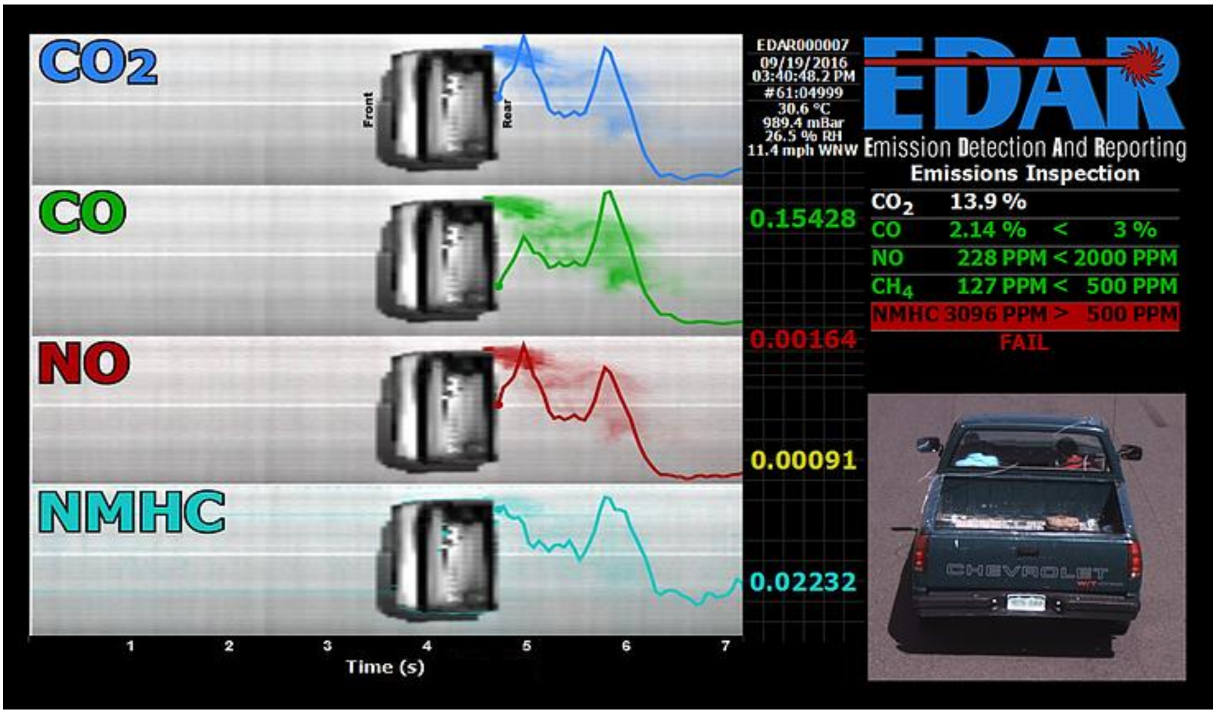


Figure 2. Vehicle measurement screen from EDAR monitoring software.

OPUS:

This section briefly describes the main features of the OPUS system from OPUS RSE (Remote Sensing Europe), further details can be found elsewhere ([7], www.opusrse.com)

The OPUS remote sensing system is based on dispersive infrared and non-dispersive ultraviolet spectroscopy for the measurement of emissions of vehicles as they are driven by the roadside system. OPUS' optical path is set up horizontally across the road at the level of the tailpipe exhaust. The light source(s)/detector(s) and the retroreflector are each deployed as a module on opposing road shoulders. A vehicle speed/acceleration sensor and a license plate reader complete the system.

As a vehicle crosses the optical path, the OPUS devices measure the relative concentrations of CO, CO_2, NO, NO_2, hydrocarbons (HC) and particulate matter to carbon dioxide. Figure 3 shows an example of the report that is produced by OPUS for every vehicle detected and evaluated, with the four preceding vehicles shown in an abridged way in the small pictures below the main picture. All data are combined for further data processing and analysis. Processing of OPUS data in the scope of this report has been done by OPUS.

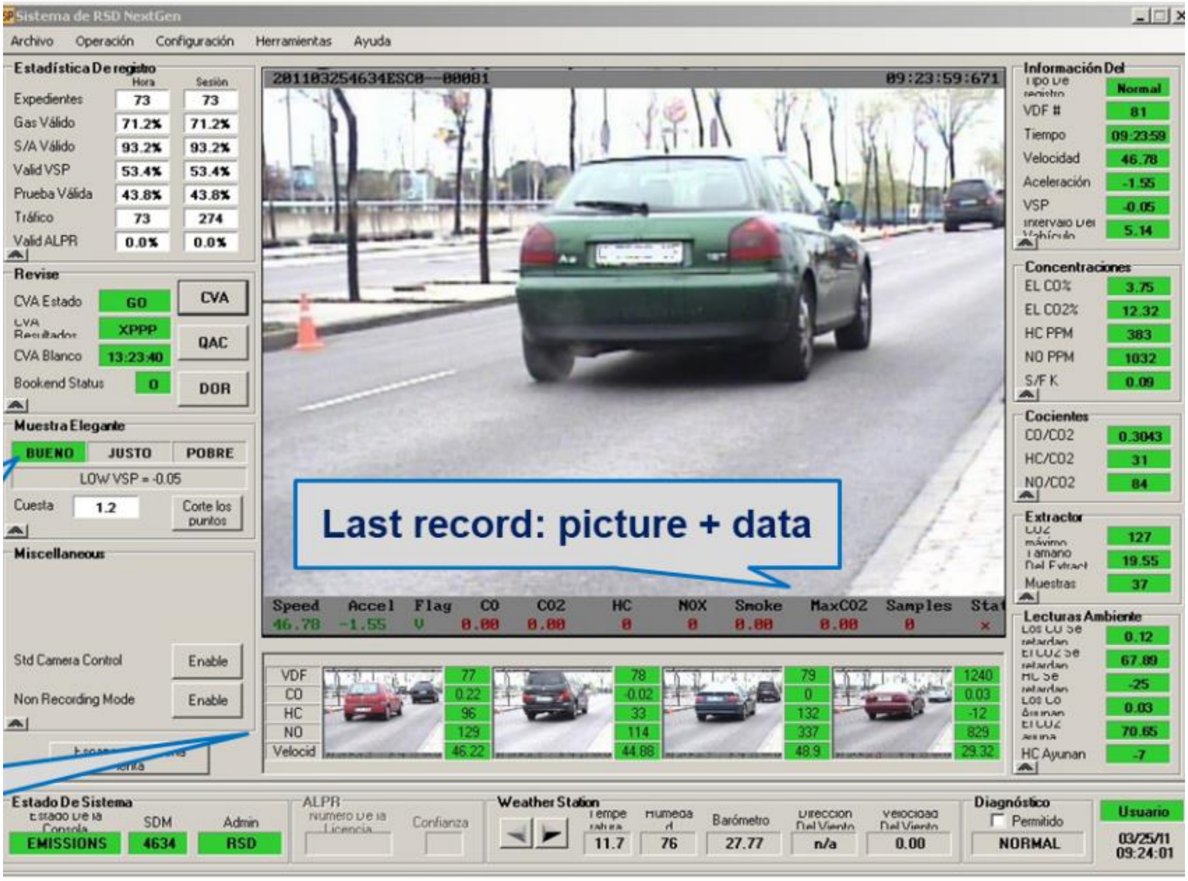


Figure 3. Vehicle measurement screen from OPUS monitoring software.

3 Overview of the test program

The two RSDs were tested under the same environmental conditions and using the very same set of vehicles and gases. The main elements and features of the test program are presented in this chapter.

3.1 JRC Reference Vehicles

The main purpose of the "Reference Vehicles" was to check the emissions measurements of the RSDs against a known method. To obtain instantaneous vehicle emissions at the RSD location, a set of reference vehicles were all equipped with PEMS. PEMS measure the gaseous concentrations in and the mass flow of the exhaust of the reference vehicles within a known uncertainty range and were considered as the reference within this study. Two types of vehicles were used:

- Electric vehicles equipped with gas bottles to simulate constant vehicle exhausts with different concentrations of CO_2 and gaseous pollutants (NO, CO, whereas NO_2 was not available) as expected under various driving conditions for vehicles with different emission standards. The synthetic gas was blown through a tube and measured with a PEMS to simulate regular tailpipe situations. The test vehicle and the installation are respectively shown in Figure 4.
- Vehicles with internal combustion engines of different types and emission standards were equipped with a PEMS (Figure 5) and used to assess the ability of the RSDs to assess emissions under dynamic driving conditions and different emission ranges compared to the electric simulation vehicle.

Vehicle characteristics are described in Table 1, photos are shown for illustration in Figure 4 and Figure 5. The PEMS used was the Semtech DS (SENSORS) for all vehicles except number 3 for which the MOVE (AVL) was installed. The sizes of the exhaust flow meters were selected to match the engine displacements.

For these vehicles, the use of the PEMS followed the relevant best available practices [17], including the verification of the PEMS equipment before and after the test (zero and span drift checks).

Table 1. JRC Reference Vehicles used during the assessment. "ICE", "TWC", "EGR" and "SCR" stand for Internal Combustion Engine, Three-Way Catalyst, Exhaust Gas Recirculation and Selective Catalytic Reduction, respectively.

Vehicle	Engine	Emission Standard	Emission Reduction Technologies	Engine Displacement [cm^3]	Power [kW]
1	Electric	N/A		-	-
2	ICE Gasoline	Euro 4	TWC	1368	57
3	ICE Diesel	Euro 6b	DPF, EGR, SCR	1968	110
4	ICE Diesel	Euro 6b	DPF, EGR, SCR	2967	184

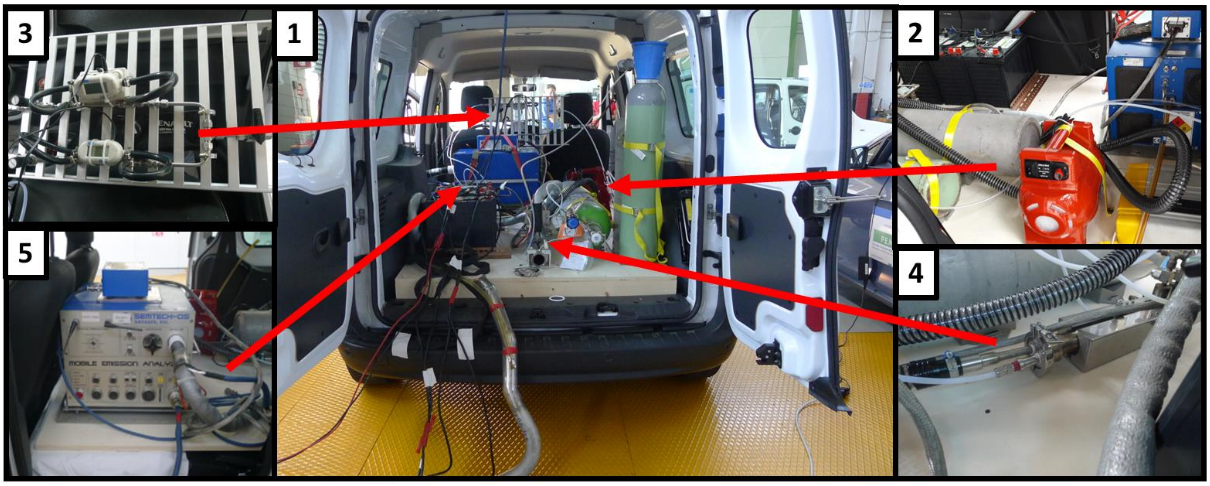
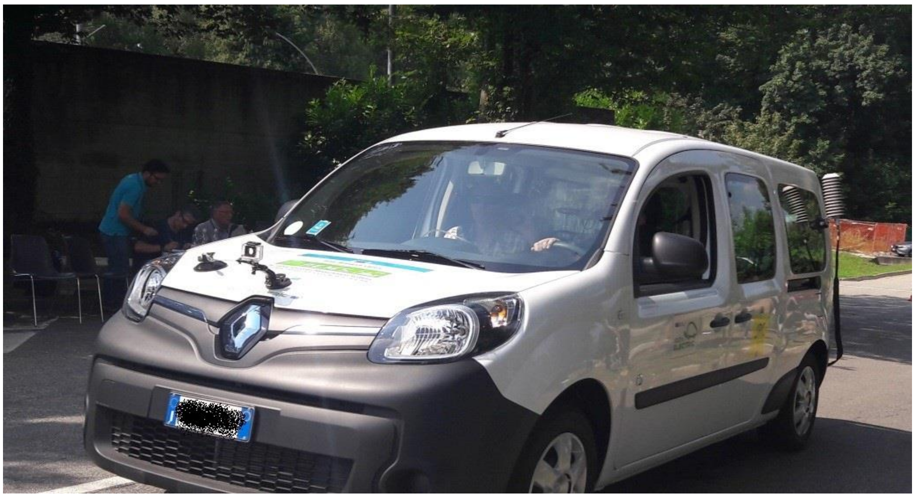


Figure 4. General outlook of the electric vehicle setup (1): Compressor (2), calibrated flowmeters for the standard gas cylinders (3), mixing module (4) and PEMS instrument (5).



Vehicle 1 - Electric with gas cyclinders

Vehicle 2 - Euro 4 Gasoline

Vehicle 3 - Euro 6b Diesel

Vehicle 4 – Euro 6b Diesel

Figure 5. Reference vehicles used for this report.

3.2 Other vehicles

Several other vehicles - whose technical details (fuel, emissions standards, etc.) were known - were selected and passed through the two RSDs. The complete list of test vehicles is provided in Table 2.

Table 2. Characteristics of the other vehicles. Vehicles category M1 except when mentioned differently. "LCV" stands for Light Commercial Vehicle. "L-Cat" stands for Light Category vehicles. "LPG" stands for Liquefied Petroleum Gas.

Vehicle #	Fuel Type	Euro Standard	Engine Capacity [cm^3]	Power [kW]
1	diesel	Euro 3	1398	50
2	diesel	Euro 3	2800	94
3	diesel	Euro 3	2476	73.4
4	diesel	Euro 3	2179	74
5	diesel	Euro 3	1870	75
6	diesel	Euro 3	1753	66
7	diesel	Euro 3	1995	85
8	diesel	Euro 4	1560	80
9	diesel	Euro 4	1560	80
10	diesel	Euro 5	1968	132
11	diesel	Euro 5	1968	103
12	diesel	Euro 5	1968	103
13	diesel	Euro 6	1560	88
14	diesel	Euro 6	1968	110
15	diesel	Euro 6	2967	184
16	diesel	Euro 6	1969	88
17	diesel	Euro 6, LCV Class 3	1995	96
18	diesel	Euro V, truck	11000	338
19	gasoline	Euro 4	1368	57
20	gasoline	Euro 4	1599	90
21	gasoline	Euro 4	2171	125
22	gasoline	Euro 5	1149	74
23	gasoline	Euro 5	1199	60

24	gasoline	Euro 6	1598	60
25	gasoline	Euro 6	999	52
26	gasoline	Euro 6	875	62.5
27	hybrid electric / gasoline	Euro 6	1798	73
28	LPG / gasoline	Euro 0	1100	44
29	LPG / gasoline	Euro 5	1598	60
30	gasoline	Euro 2, L-Cat L7e	976	15
31	gasoline	Euro 3, L-Cat L3e	998	73
32	gasoline	Euro 3, L-Cat L3e	394.9	23

Some special vehicles were also selected and prepared to assess the potential of RSDs to detect malfunctions or tampering of the emissions control systems:

- A light commercial vehicle (LCV - #17, van) whose DPF was tampered for the purpose of the project and whose PM results were compared to the ones from vehicles equipped with a properly functioning DPF.
- A heavy-duty truck (#18) whose urea injection was activated or de-activated using a tampering device plugged onto the vehicle ECU.

3.3 JRC Test Conditions

The two RSDs were installed on one of the roads of the JRC site in Ispra, Italy. For the selected location, the road slope is positive for approximately 300 meters and the vehicle speeds could range from low up to 50 km/h in accordance with the JRC site road safety regulations.

The systems were installed according to the existing recommendations [11] and in full agreement with the RSD instrument providers. Both systems were located in a straight line and with distances of 5 to 15 m between them. The measurements were carried out "uphill", i.e. with the vehicles accelerating. Such a configuration ensures that the vehicles operated at this location under engine load. These settings resulted in a relatively narrow range of conditions in terms of vehicle speed and acceleration.

The testing conditions are summarised in the Table 3 below and the photos with the installation of the RSDs are shown in Figure 7. All ambient data were provided by the JRC's Atmospheric Observatory (abc-is.jrc.ec.europa.eu) located on the JRC Ispra site.

Vehicles were passing the RSDs several times, partly under more similar (reference vehicles), and partly under distinctively different driving conditions (other vehicles) in order to cover a wide range of pollutant ratios during this exercise.

Table 3. Testing conditions

Item	Value
Range of vehicle speeds [km/h]	9 to 50
Range of vehicle positive accelerations [m/s2]	0 to 8
Ambient temperature range [degrees Celsius]	25 to 32
Average road slope [%]	4.6
Latitude [degrees]	45.809388
Longitude [degrees]	8.637853
Ambient air background NO [μg/m^3]	< 1
Ambient air background NO_2 [μg/m^3]	5 to 8
Ambient air background CO [mg/m^3]	< 0.3
Ambient air background CO_2 [mg/m^3]	680 to 710

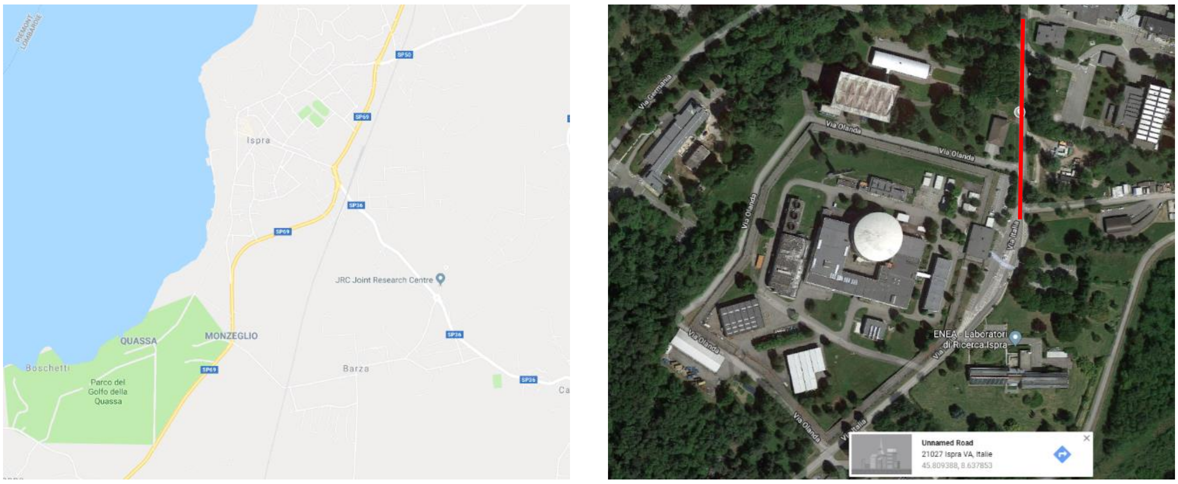


Figure 6. Location of the test site (Map).

Figure 7. Installation of EDAR (Left) and OPUS (Right) RSDs.

3.4 Instruments verification

In this project, the off-site equipment checks were conducted by the instrument providers prior to the test campaign, according to traceable procedures, such as for instance recommended by US-EPA in their guidance on Remote Sensing Devices [11]. The on-site checks were conducted by each instrument providers own procedures.

4 Data processing

4.1 Introduction

During the measurement campaign, the responsibility to install, to verify the equipment and to collect the data from the respective RSD was attributed to the two instrument manufacturers (HEAT, OPUS). The JRC provided the test vehicles, including the PEMS and its data processing where relevant, and assessed the data independently upon the completion of the measurements. The collected data was screened and checked by the instrument providers exclusively to verify the correct correspondence between every single RSD measurement and a given vehicle.

4.2 RSD Results

The list of the parameters recorded by each system that are necessary for the processing and interpretation of measurement data is provided in Table 4. In addition, both systems record further ancillary and diagnostics data that are potentially useful for quality assurance purposes.

As a reminder, the RSD exhaust gas measurements are based on optical spectroscopy with an unknown and highly dynamic probing volume, only ratios to CO_2 can be directly obtained.

Table 4. Parameters recorded by the RSDs for use within the scope of this report.

Parameter	EDAR	Opus
Time and date	X	X
Ambient temperature, humidity and pressure	X	X
CO/CO_2 ratio [% / %]	X	X
NO/CO_2 ratio [ppm / %]	X	X
NO_2/CO_2 ratio [ppm / %]	X	X
PM Opacity	X	X
Vehicle speed [km/h]	X	X
Vehicle acceleration [km/h/s]	X	X
Time interval between passing vehicles (one-way) [s]	X	X
Vehicle number plate, incl. photo	X	X

4.3 Time alignment of RSD and PEMS data for reference vehicles

In order to compare RSD derived exhaust gas ratios to PEMS data that has been used for this report, the proper time alignment of both independent datasets is crucial. The RSD takes a snapshot of the pollutant to CO_2 ratios as produced and exiting the tailpipe of the vehicle at the moment when it drives by the measurement system. From the PEMS data stream, the measurement result for the very same exhaust should be taken to compare it to the RSD data. If this would not be the case, different exhaust plumes corresponding to different engine states would be compared by the two systems and this would result in no correlation of the two systems. It has to be noted that data alignment of the two system types (PEMSs and RSDs) was vehicle dependent, as it was linked to i/ the vehicle after-treatment shape, ii/ the exhaust flow rate in the testing condition described in Table 5, so the vehicle engine capacity and power. Consequently, time alignment was conducted separately for every combination PEMS/vehicle, and for every pollutant. However, once the time shift was calculated for the combination PEMS/vehicle and for a specific pollutant, it was applied consistently on the whole test data stream.

The only exception is the electric vehicle simulating exhaust with different gas mixtures; there the gas ratios remain constant for several seconds covering the pass-by of the RSDs. Therefore, it is irrelevant which of the PEMS data points is compared to the RSD measurement and in fact it is impossible to obtain a time alignment through correlation.

The following data processing steps have been performed to obtain the time alignment:

1) Rough time alignment of the two data streams using markers inserted manually by the co-pilot in the PEMS data stream during the measurement for all passings of the vehicle at the RSD measuring location (cf. vertical grey lines in Figure 8).

2) Projection of the RSD computer time on the 4 Hz PEMS modal signal (cf. red points in Figure 8).

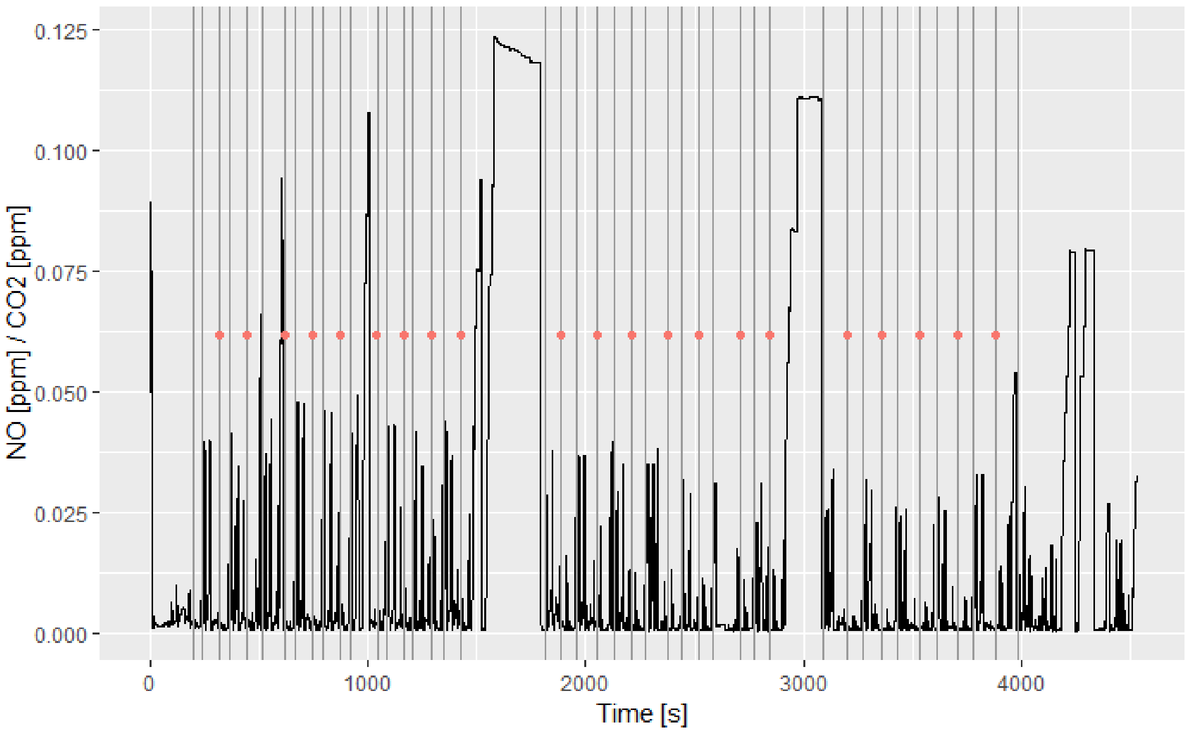


Figure 8. PEMS NO/CO_2 data stream from the reference vehicle 4. Vertical grey lines stand for the markers manually inserted by the co-pilot present in the reference vehicle during the measurement. Red points stand for the RSD valid measurement points obtained after internal quality check.

3) Maximization of the correlation between RSD and PEMS derived pollutant to CO_2 ratios by moving the PEMS time in 0.25 s steps over a -/+ 15s window with a fixed RSD time (cf. vertical red lines in Figure 8).

4) Calculate 1 s averages of the PEMS pollutants data around this time shift.

These time optimized PEMS pollutants data with 1 s time resolution are paired with the respective RSD data for the reference vehicles and pollutants for further analysis of the data.

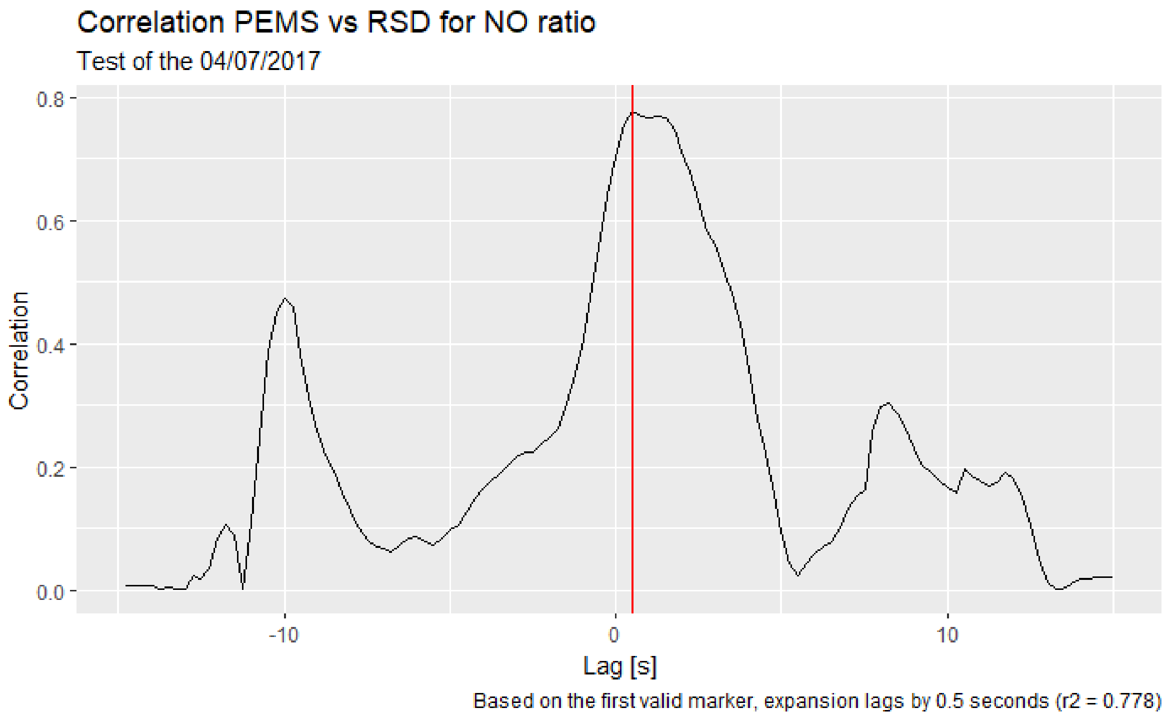


Figure 9. Optimization of the correlation of the NO/CO_2 RSD measurement points against the 4 Hz PEMS data stream for reference vehicle 4. The RSD/PEMS time lag was defined when the maximum correlation was obtained, for every combination PEMS/reference vehicle and for each pollutant.

5 Analysis of measurement results

5.1 Evaluation principles

To pursue the overall objective of the study (i.e. to assess the potential of Remote Sensing Devices to check vehicle emissions), the approach described in the following section was adopted.

The RSDs provided a snapshot of the vehicle's emissions at the measurement point. The conditions in the exhaust plume cannot be kept stable for all vehicles, due to the wind and weather variations. Additional variability occurs for the combustion engines as the real vehicle emissions vary as a function of the operating conditions (including for instance the ambient conditions, the vehicle conditioning and the driving dynamics). These effects are sketched in Figure 10, which shows that the actual vehicle emissions at the RSD measurement location may vary within a range, that range being much smaller when the exhaust gas composition is simulated and kept constant with gas bottles and control valves (Reference Vehicle 1).

The general principle for the correlation exercise between RSD and PEMS was that the multiple measurements made with the reference vehicles were treated individually.

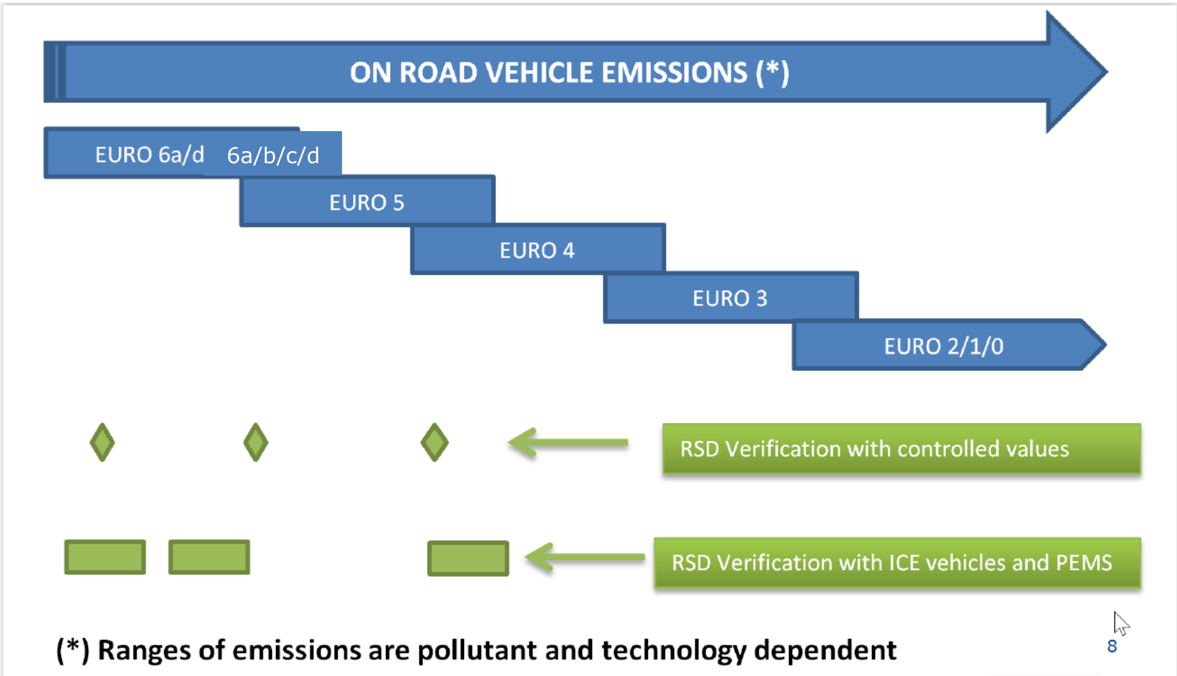


Figure 10. General approach for RSD versus PEMS comparison.

As the first step, the performances of the RSDs were assessed against the reference vehicles with known exhaust gas ratios.

The electric vehicle with a release of a constant mixture of simulated exhaust gas provides predictable and well defined reference measures. The ICE vehicles with PEMS on the other hand allowed for a much broader range of emissions as observed during real driving, extended to other regulated vehicle exhausts, and dynamic driving situations.

The second step comprised the gathering of RSD data from several vehicles across different Euro standards at various driving conditions in order to have a broader set of RSD measurements that can be expected for a deployment of RSDs at similar road situations.

As the third and last step we try to extrapolate the expected RSD observations to the latest Euro 6d-Temp vehicles for which PEMS measurements have been done at the JRC after the

RSD test presented here. This should provide a projection of RSD results for clean vehicles equipped with the latest pollution reduction measures.

5.2 PEMS versus RSD correlation - Results for reference vehicles

The reference vehicles with PEMS have been driven in a variety of speeds and acceleration – within the limitations of the chosen location inside the JRC Ispra premises – in order to measure a broad range of pollutant concentrations to CO_2 ratio to compare RSDs with PEMS.

The results of the comparison for the different exhaust gases NO, NO_2 and CO are presented in the following sections. Due to the lack of PN PEMS equipment, the Particle measurement validation could not be conducted during the measurement campaign with reference vehicles.

In the following sections, results from the two RSDs are presented in an anonymised way and labelled RSD 1 and RSD2. Both systems have specific internal quality checks applied to each data point to report it as valid or invalid according to criteria defined by the manufacturer. This results in PEMS data points that are used for establishing the correlation with one RSD, but not for the other one. This is especially evident in Figure 11 for vehicle 2 where RSD 1 and PEMS have a data point with high NO concentration that is absent in the plot for RSD2.

5.2.1 NO validation

The comparison of RSD measurements versus PEMS results for the different vehicles are shown in Figure 11 and the related linear fits summarized in Table 5.

Emissions of NO were simulated with the electric vehicle (#1) in a range for NO to CO_2 ratios from 20 [ppm / %] to 60 [ppm / %]. Lower ratios, though desirable to cover also low NO emitting situations, were not obtained due to the available gas cylinders and settings of the test gas delivery system.

As expected from the power train technology used in the different cars, diesel engines (vehicles 3 & 4) produce a higher NO to CO_2 ratio compared to the gasoline vehicle. Combining all tests, the reference vehicles covered the generation of a broad range of NO to CO_2 ratios from a few [ppm / %] up to 60 [ppm / %] and thus mimicked the behaviour of more and less polluting vehicles.

Both RSD measurement technologies correlate very well with PEMS data obtained at the same location and show a very linear relationship (Table 5) across the entire scale spanned with the combined data from all reference vehicles. Combining the per vehicle data, the PEMS vs RSD relationships result in slopes of 1.03 (+/- 0.01) & R^2 = 0.98 and 0.92 (+/- 0.01) & R^2 = 0.97, for RSD 1 & 2 respectively (Table 5). The values in parenthesis are the standard errors of the slope for the linear fit of RSD to PEMS data.

Table 5. Coefficients from linear model fit between RSDs and PEMS NO/CO_2 ratios using the data points from all reference vehicles.

all vehicles combined	Intercept [ppm / %]	Slope	Standard error of Slope	R^2 of the fit
RSD 1	0.06	1.03	0.014	0.98
RSD 2	0.13	0.92	0.015	0.97

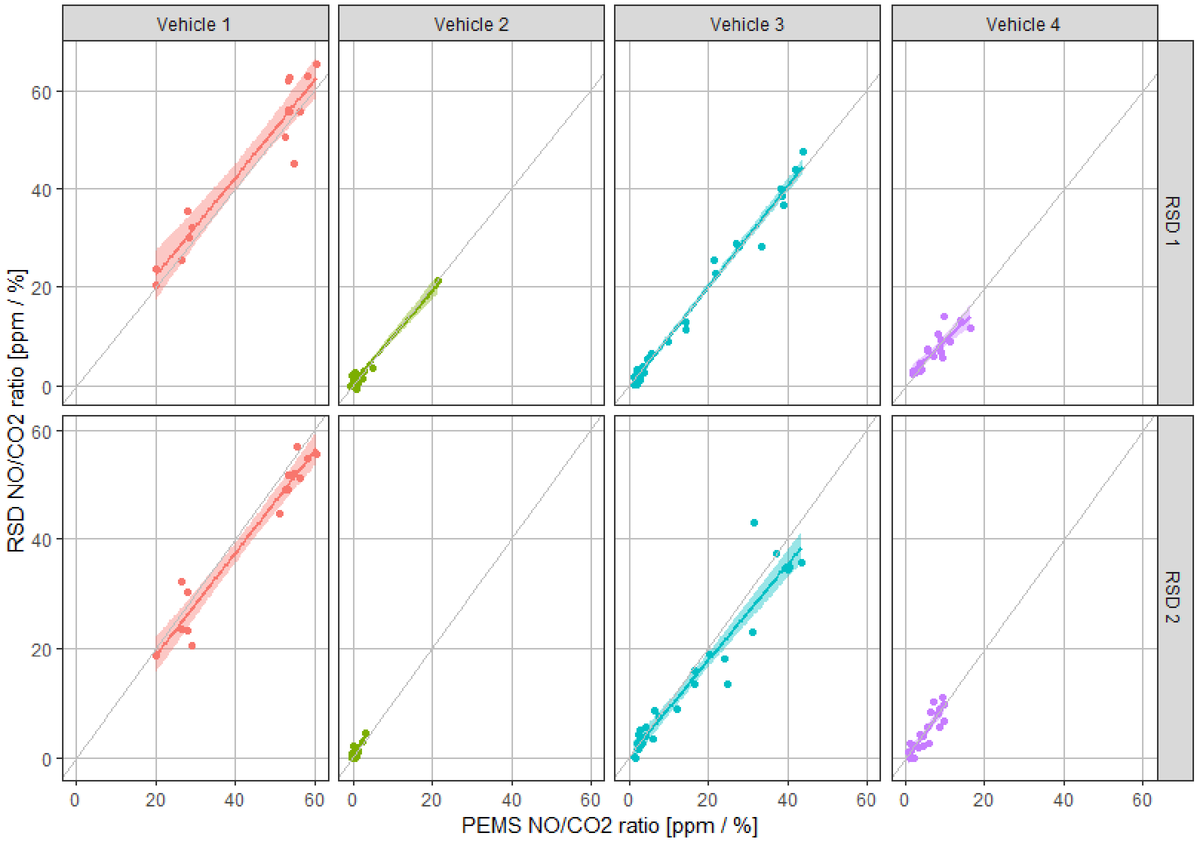


Figure 11. Scatter plot for NO to CO2 ratios between PEMS and RSD measurements for the different reference vehicles (1-electric, 2-gasoline, 3 & 4-diesel) and RSDs. Grey lines are the 1:1 lines.

5.2.2 NO_2 validation

For the NO_2 measurements, only vehicles 2, 3 & 4 were used as the electric vehicle was not equipped with NO2 reference gas for controlled release. The comparison of RSD versus PEMS results for the NO2 to CO2 ratios are combined for all vehicles in Figure 12.

The concentration of NO2 in the direct vehicle exhaust plume is very low and reaches as a maximum only approx. 12 [ppm / %] as measured with PEMS. This is a factor of 5 lower than the maximum ratio of NO to CO2 described in the previous section. Furthermore, it is clearly at the limit of detection as also negative ratios are reported. When there is no detectable NO2 present in the exhaust, one would expect half of the measurements to be positive and the other half negative for the raw measurement data.

Even with significant measurement noise, averages over many readings can give a valuable picture of fleet averages. The slope values for a linear model fit to the PEMS observations are both quite reasonable given the low concentrations with RSD 1 measuring about 15% higher and RSD2 about 18% lower than PEMS. Neither system shows a significant offset from zero*.*

R^2 is significantly worse compared to the NO measurements. Excluding the negative values for RSD 1 would not improve the relationship in general, but slightly increase the fleet average. RSD 2 seems to capture low NO2 ratios slightly better, but approaches its limit of detection at these low values as well.

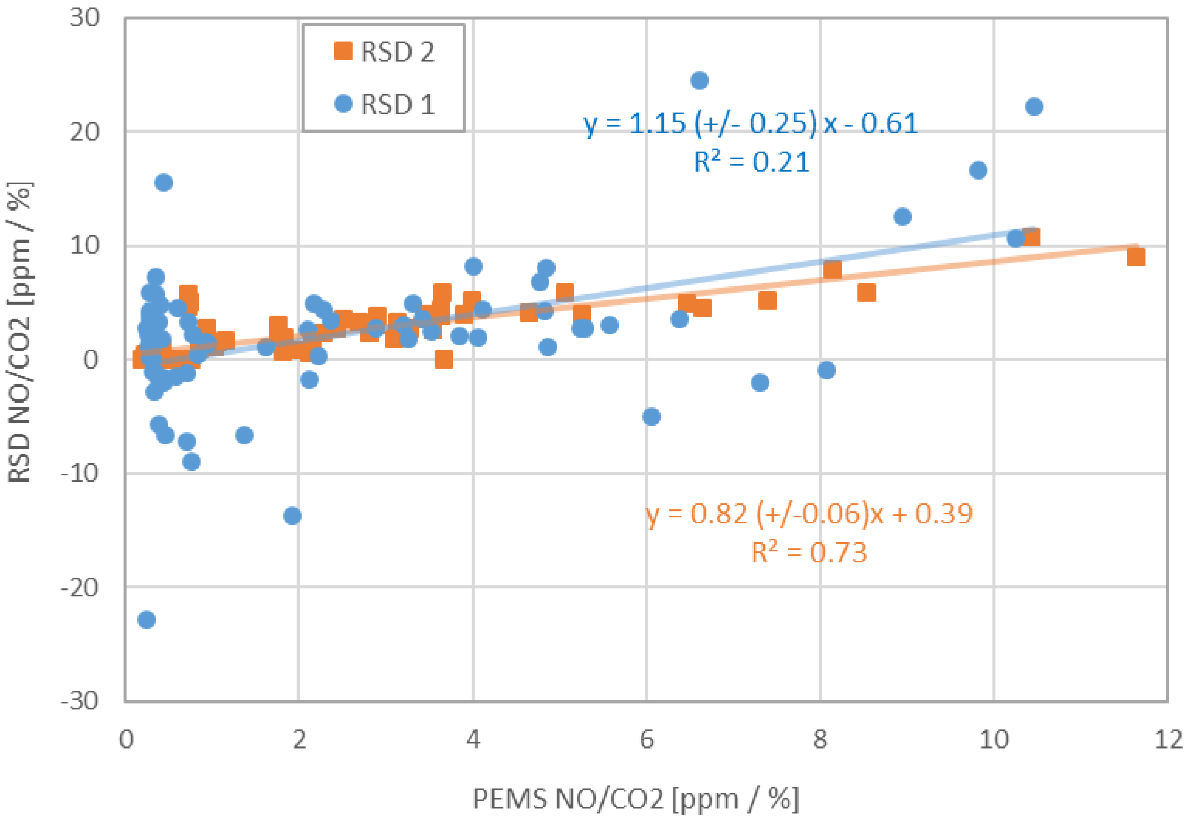


Figure 12. Scatter plot for NO_2 to CO_2 ratios between PEMS and RSD measurements, combined for reference vehicles. The linear fit includes the standard error of the slope.

5.2.3 **CO validation**

For CO, measurements from all 4 reference vehicles were used again to compare the CO to CO_2 ratios obtained with the two RSDs versus PEMS. The combined data are shown in Figure 13. The obtained values span a large range from very low ratios near the observation limit of all three systems to high values up to 0.3 [% / %] from the gasoline vehicle shown in the inset.

Both RSDs correlate very well with the PEMS and result for linear model fits in slopes of 0.88 (+/-0.02) & R^2 = 0.96 and 0.97 (+/-0.01) & R^2 = 0.99, for RSD 1 & 2 respectively. At low values close to the observation limit, RSD 1 shows a slightly higher variability.

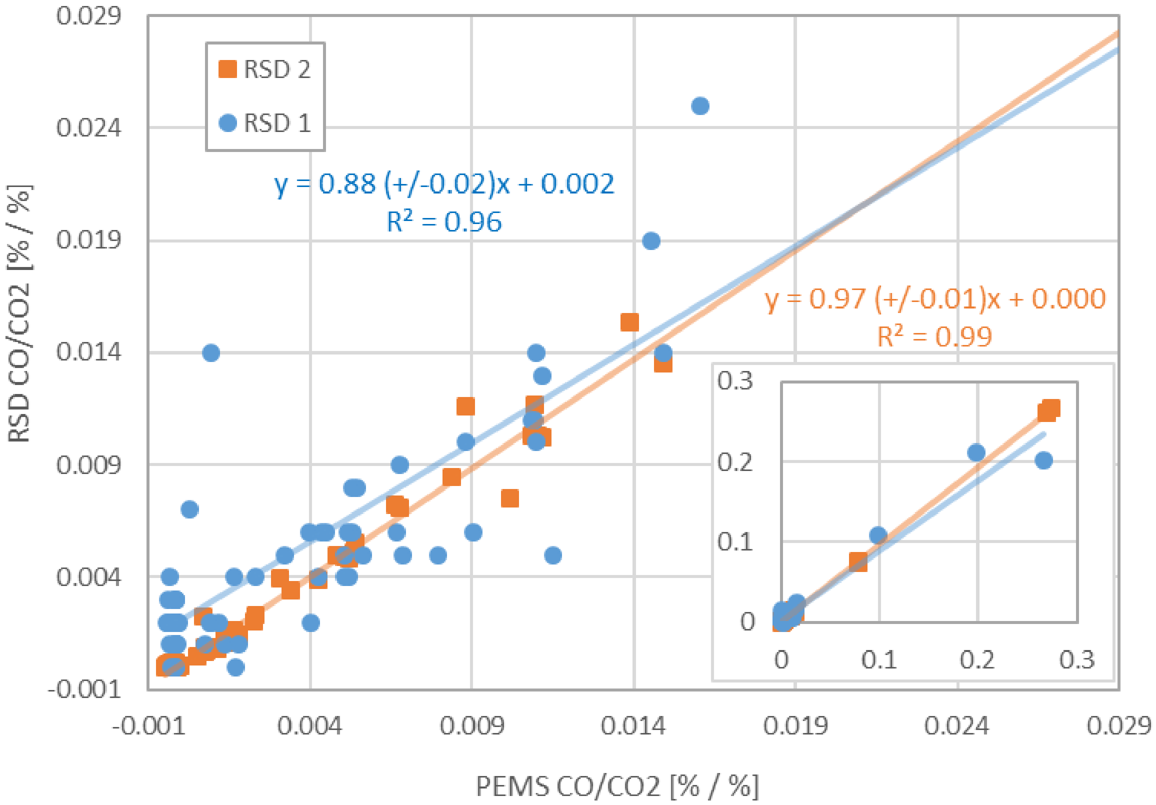


Figure 13. Scatter plot for CO to CO_2 ratios between PEMS and RSD measurements, combined for all reference vehicles. The inset includes the high ratios observed on some driving situations for the gasoline vehicle. The linear fit includes the standard error of the slope.

Summarizing the results for the reference vehicles, the comparison between PEMS and the RSDs has demonstrated good agreement of the different measurement methodologies for the quantification of the main vehicle emissions NO and CO. The measurements covered a wide range of ratios of the pollutant to CO_2, up to approx. 60 [ppm / %] for NO and 0.3 [% / %] for CO.

Regarding the third gaseous pollutant measured, NO_2, for the vehicles tested the emissions levels were a factor of 5 lower than for NO and clearly on the limit for the detection by the RSD systems. Higher NO_2 emission levels were not available to test the systems' behaviour there.

5.3 Overview of emissions results - All vehicles

This chapter presents the results of all 32 vehicles passing the remote sensing devices. The aim was to cover many different driving situations with these vehicles within the safe driving limits of the location. For the data evaluation and for proper use of the RSD methodology, only uphill driving situations were considered. The vehicles passed the two systems 611 times in total. After internal data quality check performed by each RSD manufacturer for every pollutant, between 495 (for the NO / CO_2 ratio) and 243 (for the PM opacity) valid data points were obtained.

Figure 14 aggregates the different vehicles across fuel types (gasoline, diesel, LPG & hybrid) for the pollutant ratios of CO, NO, and NO_2 relative to CO_2; PM by opacity as provided by the manufacturers. In addition, the two special vehicles with not properly functioning exhaust after-treatment systems, i.e. tampered diesel particle filter (no DPF) and blocked selective catalytic reduction system (no SCR) are shown separately. The results for the two RSDs are combined. Valid RSD readings per fuel type stretched from 3 for the NO measurement of the hybrid to 289 for all diesel vehicles.

The boxplots of the pollutants to CO_2 ratios are taken as the logarithm to cover the large variability of the single measurements. The red line indicates the median of all observations for a fuel type and the box the 25 and 75 percentiles. The whiskers depict 1.5 times the interquartile range and the red crosses single values outside these boundaries.

The large variability for instantaneous pollutant emissions due to different vehicle technologies and driving situations that span up to 4 orders of magnitude (logarithmic scales) is evident from the boxplots again. Focussing on the median values, gasoline vehicles generate a significantly higher CO / CO_2 signature than diesel vehicles, whereas for NO / CO_2 diesel vehicles give higher values than gasoline fuelled vehicles. For the NO_2 / CO_2 ratio and PM, the distribution of emissions are very similar for both gasoline and diesel engine technologies.

Despite the significant difference in the median of the observed values for CO / CO_2 and NO / CO_2, it is important to point out that any single observation for a diesel car can fall within the typical fleet behaviour of diesel or gasoline vehicles and the other way around.

Looking at the deliberately tampered vehicles, the one with a not functioning Diesel Particle Filter (DPF) has a significantly higher PM compared to the median of the properly functioning diesel cars. Looking though at the range of measured data points, they all fall within the range also observed for all diesel vehicles. For what regards the vehicle with disabled Selective Catalytic Reduction (SCR) system, the NO / CO_2 ratios are significantly higher compared to the same vehicle's operation with properly functioning SCR and also higher than the 75 percentile of all other diesel vehicles. For a single measurement of the tampered vehicle though, it still might fall into the extreme ranges of observed values for both, the same vehicle under proper operation and all properly emitting diesel vehicles.

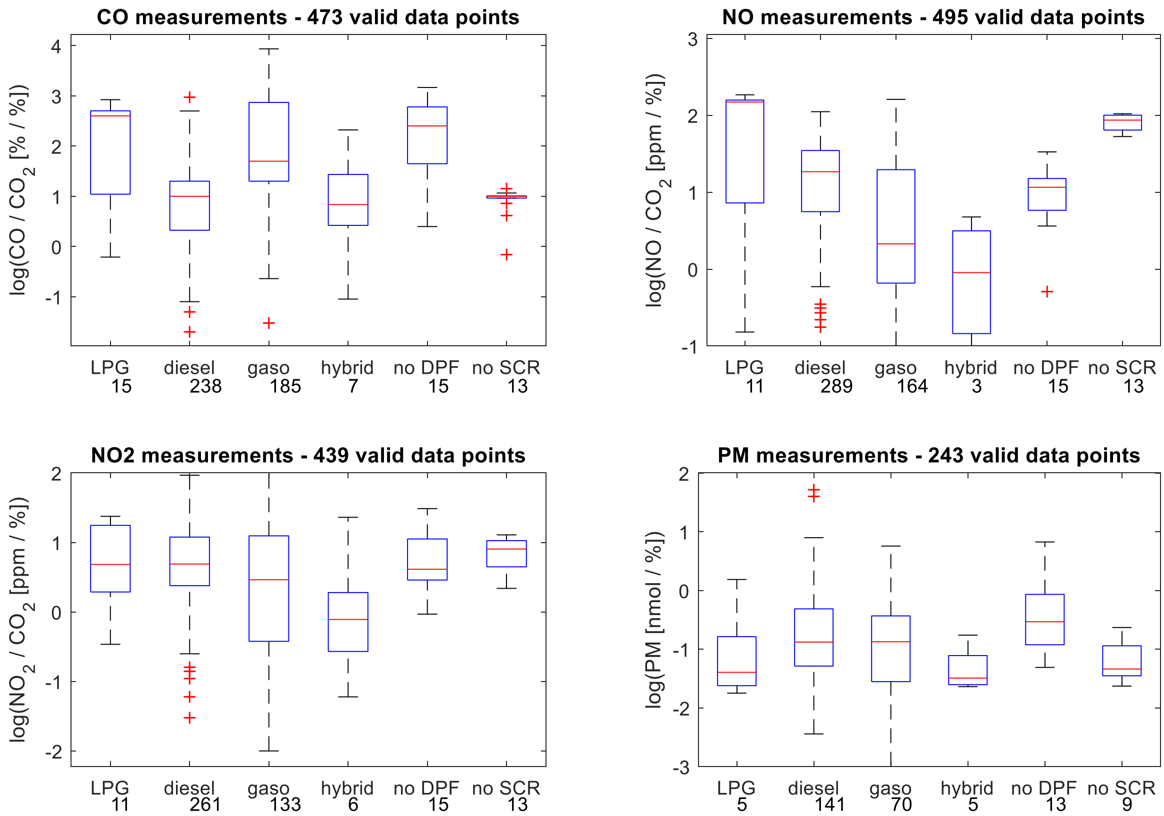


Figure 14. Pollutant ratios (CO, NO, NO_2 and PM – top left to bottom right) measured with both RSD for all vehicle passes and aggregated for each fuel type. The red line inside the boxes depicts the median, the box the 25 and 75 percentiles, the whiskers the 1.5 times interquartile ranges and the red crosses single values outside these ranges. Numbers indicate the valid RSD readings for each category, "gaso" stands for gasoline.

To illustrate the potential to observe with RSDs the evolution of the emission behaviour for vehicles with different standards, Figure 15 focuses on the RSD observations for diesel vehicles from Euro 3 to 6, plus the heavy-duty vehicle with Euro V and the tampered ones. As the driving conditions were not restricted to very similar behaviour for the different vehicles and passings at the measurement point, the observed pollutant to CO_2 ratios were quite broad again across all Euro standards.

Looking at CO, all vehicle categories show very similar ratios except the single Euro 6 vehicle with tampered DPF having significantly higher emissions. The tampered vehicle shows similar levels of PM as Euro 3 or 4 diesel vehicles. It has to be reminded that this Euro 6 diesel vehicle is the only Light-Commercial (Class 3) included in the test fleet (cf. Vehicle 17 in Table 4).

Regarding NO and focussing on the median of all observations, Euro 6 vehicles show lower values under the conditions present compared to the other categories, and Euro 5 higher ones. The tampered Euro V heavy duty vehicle with switched-off SCR system results in significantly elevated NO and also elevated NO_2 ratios compared to measurements with the system in function.

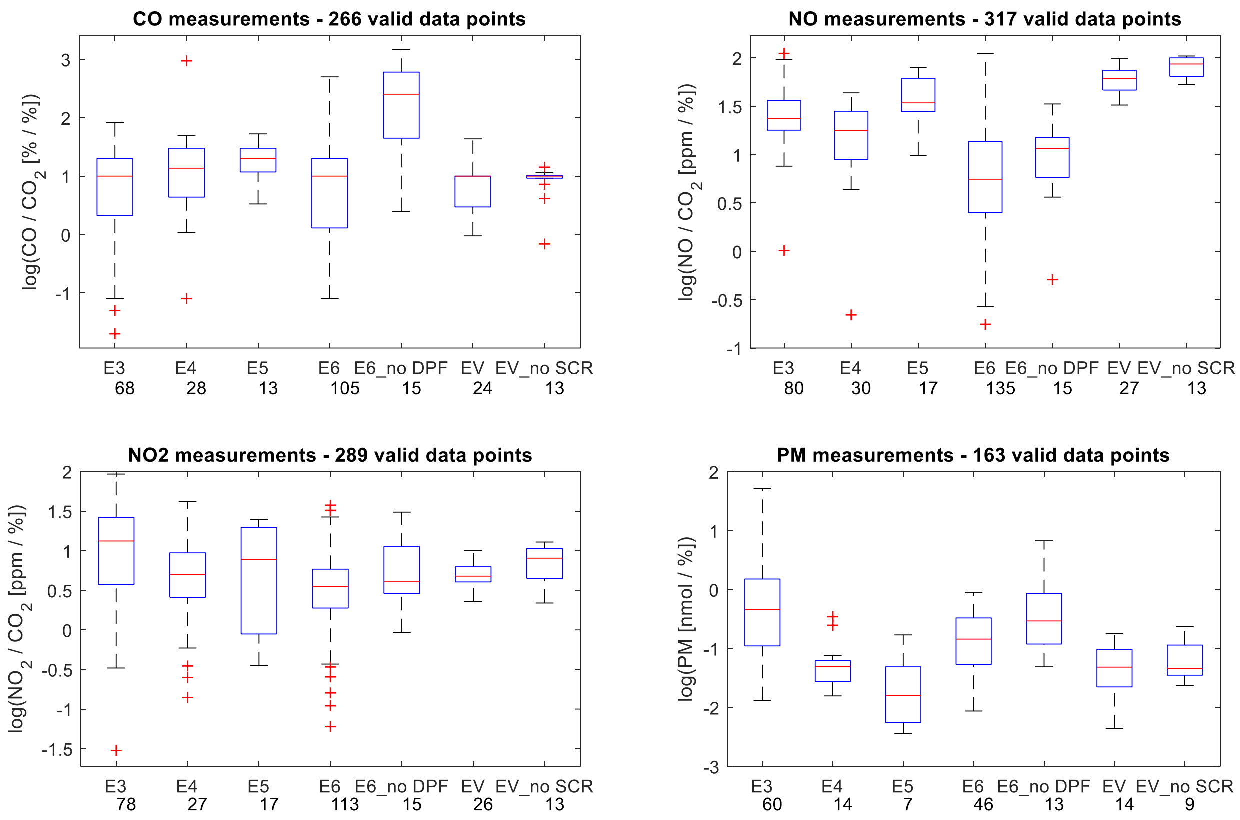


Figure 15. Diesel vehicles grouped for the different Euro standards. For explanation of the boxplot see Figure 14 above. "EV" stands for Euro V.

5.4 Projected observations for Euro 6 vehicles

To place the RSD performance in comparison to emissions that are expected from latest EURO 6 compliant vehicles on the road, instantaneous pollutant to CO_2 ratios from recent PEMS RDE tests performed at the JRC have been calculated.

The data source consists of 426 PEMS test drives from 59 different vehicles performed during 2016 and 2018 ([18] plus not yet published data from 2018 testing). Most PEMS drives were performed with the AVL MOVE system. Table 6 gives an overview on the specific vehicles that are compared to the vehicle classes in Figure 16. They represent a medium, dirtiest and cleanest vehicles in the dataset per engine technology. To mimic conditions for the PEMS tests that are similar to the RSD comparison setup (Table 3 on page 12), the instantaneous PEMS data have been filtered for the following criteria:

- Vehicle speed between 30 and 60 km/h, and
- Road slope between 5 and 7 %, and
- Exhaust gas flow rate higher than 20 % of the maximum exhaust flow measured.

This filtering results in a total of approx. 33k instantaneous PEMS data points of 1 s from the 59 vehicles for which the pollution ratios to CO_2 have been calculated.

Table 6 summarizes the vehicle emission characteristics, including the CO and NO_x emissions measured during valid RDE trips for some selected vehicles. For detailed information on these vehicles and their general emissions behaviour, the reader is referred to [18] and [19]. The median ratios of CO & NO to CO_2 have been calculated for all PEMS events of the respective vehicle. These vehicles represent already a rather comprehensive range of CO and NO_x emissions for both gasoline and diesel fuels.

Table 6. Specific vehicles compared to pooled emission standards for pollution ratios during PEMS events. CO & NO_x RDE refer to the measured pollutant emissions during valid RDE trips for the respective vehicle. CO & NO to CO_2 ratios are medians over all filtered PEMS events for the respective vehicle.

Vehicle Code	Fuel Type	Euro	CO RDE [mg/km]	NO_x RDE [mg/km]	Number of PEMS Events	Median CO/CO_2 [%/%]	Median NO/CO_2 [ppm/%]
BW014	diesel	6b	33	27	1774	*(-0.67)	0.07
VW037	diesel	6b	* (4)	137	1528	* (-1.08)	7.18
RT011	diesel	6b	86	1723	375	1.05	77.67
OL001	gasoline	6b	764	92	454	6.95	0.36
CN003	gasoline	6d-Temp	59	56	696	0.93	1.41
RT010	gasoline	6b	3667	12	706	21.46	0.06

* problem with analyser during some trips and concentrations close to limit of detection

5.4.1 **Projected NO observations**

In order to assess the capacity of RSDs to detect potentially high emitting vehicles and discriminate them from vehicles complying with the respective emission standards, the cumulated probability distributions as observed for a range of NO-to-CO_2 ratios is plotted in Figure 16. It is shown for diesel vehicles of different emission standards, as averages, ranging from Euro 5 to 6d-Temp. In addition, it is also plotted for single low NO emitting (BW014), intermediate (VW037) and high emitting (RT011) diesel vehicles.

Although single observation points for NO-to-CO_2 ratios can fall almost into the very same range for low (BW014) to high (RT011) emitting vehicles (as also evident from Figure 15: diesel vehicles grouped for the different Euro standards), the probabilities to observe high or low ratios are significantly different for the respective vehicles. These probability distributions can serve as fingerprints.

Looking at a NO-to-CO_2 ratio of e.g. 2 [ppm / %] in Figure 16 for the cumulated probability distributions and taking this value as a threshold:

- for a high emitter, e.g. RT011, almost all NO-to-CO_2 observations would be above the threshold of 2 [ppm / %],
- for a low emitter, e.g. BW014, approx. 90% of all NO-to-CO_2 observations would be below 2 [ppm / %],
- and for a medium emitter, e.g. VW037, about 10% of all NO-to-CO_2 observations would be below 2 [ppm / %].

Now starting from a set of NO-to-CO_2 ratios observed for a single vehicle or vehicle type and using the fingerprints from Figure 16:

- if almost all observed ratios are above 2 [ppm / %], the vehicle would be classified as high emitter
- whereas if most ratios are below 2 [ppm / %], the vehicle would be classified as low emitter.

The NO-to-CO_2 ratios have been selected for specific driving situations described above in order to mimic the RSD setup. Therefore, the probability distributions plotted are only characteristic for these driving situations and only consider the vehicles used in the available RDE tests. Further generalization of such probability distributions for a wider basis of vehicles and different driving situations is subject to future work.

Figure 16 also shows on the right axis the NO ratios measured with the two RSDs during the intercomparison with all PEMS equipped reference vehicles. Keeping the logarithmic scales and different ranges for the x- and y-scale in mind, PEMS and the two combined RSD measurements show a good linear correlation over a wide range with a slope of 0.98 (+/- 0.01) and R^2 = 0.97. The very high ratios above 60 [ppm / %] were not observed, but the RSD sensors are expected to perform well also at higher NO-to-CO_2 ratios of 100-300 [ppm / %] (i.e. range > 10^2 on the x-axis) according to their specifications as reported described by the manufacturers.

Combining the RSD behaviour with the PEMS measured NO-to-CO_2 ratios, it can be expected that also RSDs would measure the probability distributions in a very similar way as PEMS. Therefore, through several RSD observations of the same vehicle or the same vehicle type, one can assign a vehicle to a higher or lower polluting class of vehicles or vehicle types, respectively. Higher polluting vehicles could then be selected purely based on RSD measurements for further and more detailed investigations.

It lies outside the scope of this report to define minimum numbers of RSD observations in order to obtain meaningful probability distributions or thresholds upon which vehicles might be classified as higher or lower polluting regarding NO_x emissions.

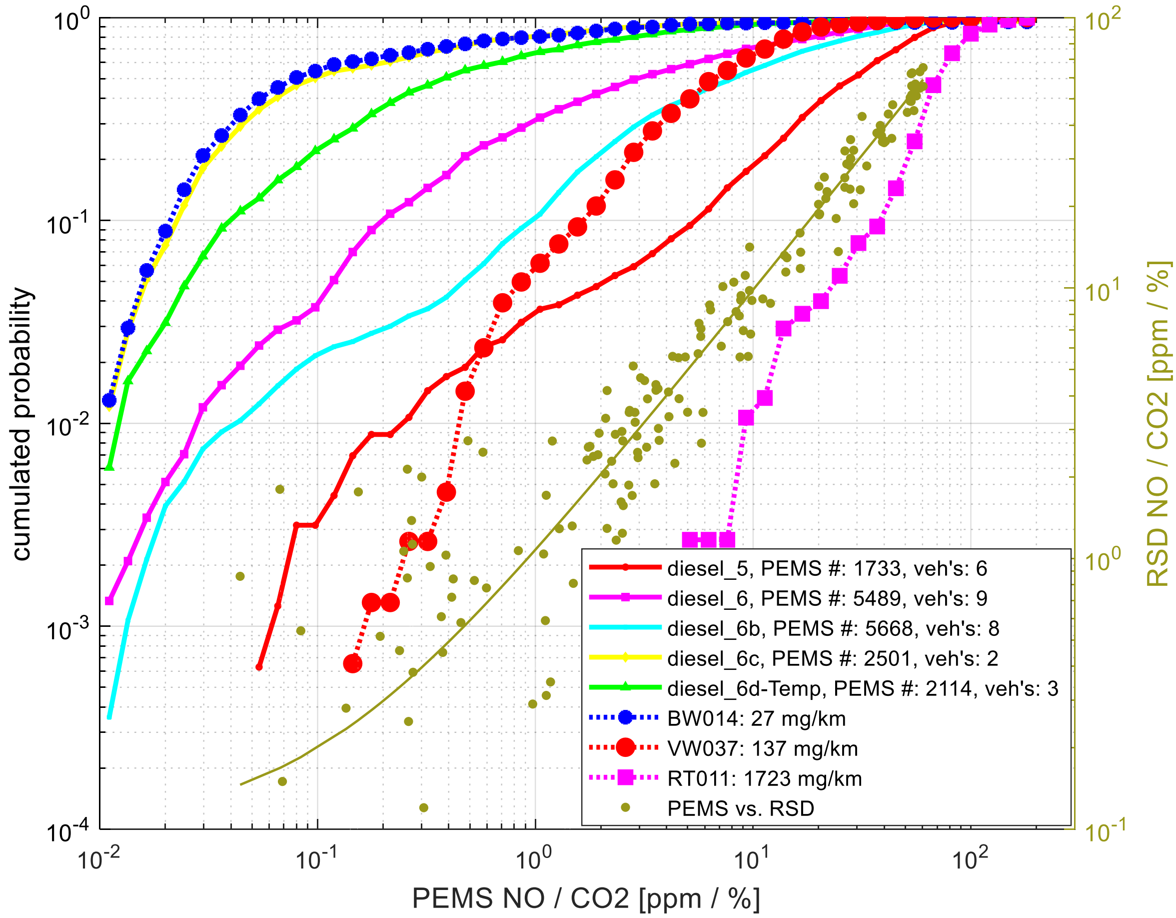


Figure 16. Cumulated probability distribution for NO-to-CO_2 ratios measured with PEMS events for diesel vehicles with different emission standards (left axis). The right axis shows the ratios measured with the two RSDs during the intercomparison with PEMS. Note the logarithmic scale for all axis, chosen to cover the large variability of the measurements. NO emissions indicated for specific vehicles in the legend originate from valid RDE trips. PEMS # = number of PEMS events used to generate the probability distribution, veh's = number of different vehicles.

5.4.2 **Projected CO observations**

The probability distributions for different vehicles for CO-to-CO_2 ratios are shown in Figure 17 in the same way as for NO in the previous paragraph, but for gasoline vehicles. In contrast to the observation for NO-to-CO_2 ratios, the probability distributions for CO are much less distinct for the gasoline vehicles complying with different emission standards. Furthermore, differences in the probabilities already start to occur at rather low CO-to-CO_2 ratios, i.e. 10-3 [% / %] and below, where the scattering between RSD and PEMS measurements is high as RSD is close to its limit of detection.

This renders it significantly more challenging, in contrast to the situation for NO, to assign vehicles to pollution classes based on only a limited number of RSD observations for CO-to-CO_2 ratios. Again taking only the example of vehicles in Figure 17, below $1x10^{-3}$ [ppm / %] fall 80% of the observed ratios for CN003, 50% for OL001, 20% for vehicle RT010.

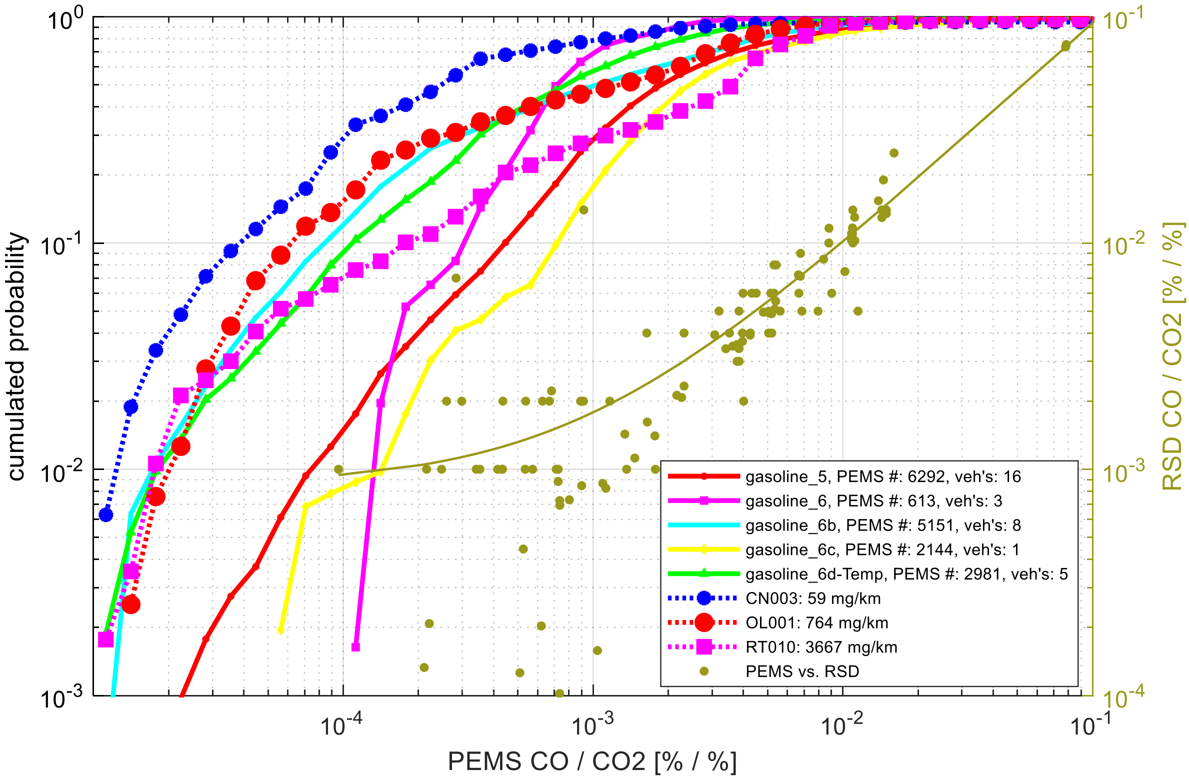


Figure 17. Cumulated probability distribution for CO-to-CO_2 ratios measured for PEMS events for differently polluting vehicles (left axis). The right axis shows the ratios measured with the two RSDs during the intercomparison with PEMS. Note the logarithmic scale for all axis, chosen to cover the large variability of the measurements. CO emissions indicated for specific vehicles in the legend originate from valid RDE trips. PEMS # = number of PEMS events used to generate the probability distribution, veh's = number of different vehicles.

One reason that contributes to the different behaviour in terms of probability distributions between CO and NO might be the filter criteria used for the instantaneous PEMS ratios that were taken into consideration in this chapter. For NO, these criteria (vehicle speed between 30 and 60 km/h, road slope between 5 and 7 % and exhaust gas flow rate higher than 20 % of the maximum exhaust flow measured) seem to select driving situations that sufficiently well represent RDE NO_x emissions. Acknowledging the small number of vehicles tested, the correlation, limited to diesel vehicles, for valid RDE trips NO_x emissions and the averaged PEMS NO-to-CO_2 ratios results in an R^2 = 0.6. For gasoline vehicles and looking at CO, the correlation gives an R^2 = 0.1. This indicates that the dominating CO emissions for gasoline vehicles are not caught at the PEMS events with the chosen selection criteria.

The limitations regarding vehicles and driving situations for which the probability distributions are shown are the same as for the NO-to-CO_2 ratios described in the previous section.

6 Conclusions

The assessment of RSDs for the observation of pollutants to CO_2 ratios has been done using a set of four reference light-duty vehicles equipped with PEMS. For CO, NO and NO_2 ratios to CO_2, the two RSDs and PEMS measurements show good correlations down to the instrumental detection limits of the remote sensing devices.

Now looking at the pollutant ratios for all 32 vehicles used to generate RSD observations, large variabilities on pollutant to CO_2 ratios have been readily observed for NO, NO_2, CO and on opacity for PM, i.e. all pollutants that were studied. This variability was observed not only across vehicle technologies, but also within the very same vehicle passing the measurement location under slightly different driving conditions. The consequence is that it is very risky to draw conclusions from single RSD observations. Therefore, several measurements of the same vehicle over time or of vehicles of the same type need to be made to draw robust conclusions about the emission behaviour of the vehicle or vehicle type, respectively.

Focussing on tampered vehicles, higher NO to CO_2 ratios and PM were observed thus demonstrating the capability of remote sensing for detecting manipulations on the emission control systems of vehicles.

To forecast what RSDs would observe for low pollutants-emitting vehicles, including the latest Euro 6d-Temp emission standard, RDE drives of several vehicles have been used to generate artificial RSD data from PEMS measurements. Calculating cumulated probabilities for pollutant to CO_2 ratios, one can obtain characteristic emission fingerprints for different emission standards and identify high and low polluting vehicles or vehicle types. These fingerprints would also be observable with RSDs, provided that a sufficient number of observations for a specific vehicle or vehicle type are available.

The RSD assessment within this study has been focused on typical traffic settings for the deployment of remote sensing devices as reported in the literature with low speed vehicles (30 – 60 km/h), uphill slope of around 5 %s and limited vehicle acceleration. This limits the observable operation parameters of vehicles to the settings described. Only very recently, RSD studies commenced on motorways to include also high velocity driving situations. Continuing to expand the vehicles' operational parameters during RSD studies further improves RSDs capability to obtain a full picture of vehicle emissions.

On the data evaluation and interpretation side, obtaining fingerprints for vehicle emission types with a wide range of RSD measurements plus the development of limits when vehicles are identified as high or low pollutant should be subject to further studies.

References

[1] Regulation (EU) 2018/858 of the European Parliament and of the Council - of 30 May 2018.

[2] Commission Regulation (EU) 2018/1832 - of 5 November 2018.

[3] Y. Huang *et al.*, 'Remote sensing of on-road vehicle emissions: Mechanism, applications and a case study from Hong Kong', *Atmospheric Environment*, vol. 182, pp. 58–74, Jun. 2018.

[4] J. Lau, W. T. Hung, and C. S. Cheung, 'Observation of increases in emission from modern vehicles over time in Hong Kong using remote sensing', *Environmental Pollution*, vol. 163, pp. 14–23, Apr. 2012.

[5] Y. Huang *et al.*, 'Emission measurement of diesel vehicles in Hong Kong through on-road remote sensing: Performance review and identification of high-emitters', *Environmental Pollution*, vol. 237, pp. 133–142, Jun. 2018.

[6] Y. Chen and J. Borken-Kleefeld, 'Real-driving emissions from cars and light commercial vehicles – Results from 13 years remote sensing at Zurich/CH', *Atmospheric Environment*, vol. 88, pp. 157–164, May 2014.

[7] M. Pujadas, A. Domínguez-Sáez, and J. De la Fuente, 'Real-driving emissions of circulating Spanish car fleet in 2015 using RSD Technology', *Science of The Total Environment*, vol. 576, pp. 193–209, Jan. 2017.

[8] G. A. Bishop and D. H. Stedman, 'A decade of on-road emissions measurements', *Environmental Science and Technology*, vol. 42, no. 5, pp. 1651–1656, 2008.

[9] D. C. Carslaw and G. Rhys-Tyler, 'New insights from comprehensive on-road measurements of NOx, NO2 and NH3 from vehicle emission remote sensing in London, UK', *Atmospheric Environment*, vol. 81, pp. 339–347, Dec. 2013.

[10] I. Schifter, L. Díaz, J. Durán, E. Guzmán, O. Chávez, and E. López-Salinas, 'Remote Sensing Study of Emissions from Motor Vehicles in the Metropolitan Area of Mexico City', *Environmental Science & Technology*, vol. 37, no. 2, pp. 395–401, Jan. 2003.

[11] 'Guidance on Use of Remote Sensing for Evaluation of I/M Program Performance (EPA-420-B-04-010,July 2004)', p. 63.

[12] G. A. Bishop, J. R. Starkey, A. Ihlenfeldt, W. J. Williams, and D. H. Stedman, 'IR Long-Path Photometry: A Remote Sensing Tool for Automobile Emissions', *Anal. Chem.*, vol. 61, no. 10, pp. 671A-677A, May 1989.

[13] D. A. Burgard, G. A. Bishop, R. S. Stadtmuller, T. R. Dalton, and D. H. Stedman, 'Spectroscopy Applied to On-Road Mobile Source Emissions', *Applied Spectroscopy*, vol. 60, no. 5, pp. 135A-148A, May 2006.

[14] K. Ropkins *et al.*, 'Real-World Vehicle Exhaust Emissions Monitoring: Review and Critical Discussion', *Critical Reviews in Environmental Science and Technology*, vol. 39, no. 2, pp. 79–152, Jan. 2009.

[15] Y. Bernard, J. German, and R. Muncrief, 'Worldwide use of remote sensing to measure motor vehicle emissions'. ICCT, 2019.

[16] K. Ropkins *et al.*, 'Evaluation of EDAR vehicle emissions remote sensing technology', *Science of The Total Environment*, vol. 609, pp. 1464–1474, Dec. 2017.

[17] V. Valverde Morales and P. Bonnel, *On-road testing with Portable Emissions Measurement Systems (PEMS) guidance note for light-duty vehicles.*, vol. EUR 29029 EN. Luxembourg: Publications Office of the European Union, 2018.

[18] M. Clairotte *et al.*, 'Joint Research Centre 2017 light-duty vehicles emissions testing', Publications Office of the European Union, Luxembourg, EUR29302EN, 2018.

[19] V. Valverde *et al.*, 'Joint Research Centre 2018 light-duty vehicles emissions testing', Publications Office of the European Union, Luxembourg, in Press, 2019.

List of abbreviations and definitions

ATP: Acceptance Test Procedure

CCM: Corner Cube Mirror

CDPHE: Colorado Department of Public Health and Environment

CO Carbon Monoxide

CO_2 Carbon Dioxide

DPF Diesel Particle Filter

EDAR Emission Detection And Reporting

EGR Exhaust Gas Recirculation

EU European Union

HC Hydrocarbons

HEAT Hager Environmental & Atmospheric Technologies

ICE Internal Combustion Engine

LCV: Light Commercial Vehicle

LiDAR: Light Detection and Ranging

LPG: Liquefied petroleum gas

NO Nitrogen Oxide

NO_2 Nitrogen Dioxide

PEMS Portable Emission Measurement System

PM Particulate Matter (mass)

PN Particle Number

RDE Real Driving Emissions

RSD Remote Sensing Device

SCR Selective Catalytic Reduction

TWC Three-Way Catalyst

WLTP Worldwide Harmonised Light Vehicle Test Procedure

List of figures

List of tables

GETTING IN TOUCH WITH THE EU

In person

All over the European Union there are hundreds of Europe Direct information centres. You can find the address of the centre nearest you at: https://europa.eu/european-union/contact_en

On the phone or by email

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

- by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

- at the following standard number: +32 22999696, or

- by electronic mail via: https://europa.eu/european-union/contact_en

FINDING INFORMATION ABOUT THE EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website at: https://europa.eu/european-union/index_en

EU publications
You can download or order free and priced EU publications from EU Bookshop at: https://publications.europa.eu/en/publications. Multiple copies of free publications may be obtained by contacting Europe Direct or your local information centre (see https://europa.eu/european-

KJ-NA-29871-EN-N

The European Commission's science and knowledge service

Joint Research Centre

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

Joint Research Centre

EU Science Hub

Publications Office of the European Union

doi:10.2760/277092

ISBN 978-92-79-11820-6