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Analyzing on-road emissions of light-duty vehicles with Portable Emission Measurement Systems (PEMS)

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Executive summary

Emissions testing in the laboratory forms an essential part of the European type-approval procedure for light-duty vehicles. The approach yields reproducible and comparable emissions data and provides clear design criteria for vehicles that have to comply with applicable emission limits. Although emission limits have become increasingly stringent in the past decade, road transport remains the most important source of urban air pollution in Europe with respect to NO_X (nitrogen oxides) and CO (carbon monoxide). Several studies have indicated that in particular on-road NO_X emissions of light-duty diesel vehicles might substantially exceed emission levels as identified during emissions testing in the laboratory. Still, a comprehensive analysis of on-road emissions of light-duty diesel and gasoline vehicles is unavailable to date.

This report addresses the existing knowledge gaps by using Portable Emission Measurement Systems (PEMS) to analyze the on-road emissions of 12 light-duty diesel and gasoline vehicles that comply with Euro 3-5 emission limits and comprise small and midsize passenger cars, two transporters, and a minivan. The selected vehicles are tested on four test routes, representing rural, urban, uphill/downhill, and motorway driving. The results indicate that the route-average NO_X emissions of diesel vehicles (0.93 ± 0.39 g/km), including Euro 5 diesel vehicles (0.62 ± 0.19 g/km), substantially exceed the respective Euro 3-5 emission limits. The route-average NO_X emissions of the tested diesel cars reach 325 ± 90% of the respective emission limits; the average NO_X emissions of individual averaging windows may reach, however, up to a factor of 14 of the respective emission limits. By comparison, the on-road NO_X emissions of gasoline vehicles as well as CO and THC (total hydrocarbon) emissions of both diesel and gasoline vehicles generally stay within Euro 3-5 emission limits. The share of NO_2 (nitrogen dioxide) in the total NO_X emissions reaches 60% for diesel vehicles but is substantially lower for gasoline vehicles (0-30%). The tested light-duty diesel and gasoline vehicles emit during on-road testing on average 189 ± 51 g CO_2/km (grams carbon dioxide per kilometre) and 162 ± 29 g CO_2/km, respectively, thereby exceeding the CO_2 emissions as specified during laboratory testing by on average 21 ± 9%. The magnitude of on-road emissions varies depending on vehicle type, operation mode, route characteristics, and ambient conditions. Cold-start emissions of both diesel and gasoline vehicles span over a wide value range; NO_X emissions exceed Euro 3-5 emission limits by a factor 2-14, CO emissions often exceed emission limits, and THC emissions are both below and above Euro 3-5 emission limits.

The PEMS equipment is reliable and provides accurate emission measurements. PEMS are able to verify the proper operation of emission control technologies under a wide variety of normal operating conditions and suitable for testing emissions of novel fuel/engine/after-treatment/powertrain technologies (e.g., parallel/serial (plug-in) hybrid vehicles. PEMS analyses, including the presented results, may also be useful for updating current transport emission models and inventories. The PEMS procedure for light-duty vehicles is, however, relatively new and requires further refinement before being applied at large scale. Future PEMS applications may particularly focus on polluting driving modes such as cold start at very low temperatures and driving at very high speed as it occurs on the German Autobahn.

The findings of this report indicate that the current laboratory emissions testing fails to capture the wide range of potential on-road emissions. A promising remedy for this problem may be attained by supplementing laboratory emissions testing with complementary test procedures such as PEMS on-road emissions testing. This report provides a first step into that direction, thereby contributing to a more comprehensive EU policy that assures compliance of light-duty vehicles with emission limits under normal conditions of use.

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List of abbreviations and units

ARTEMIS - Assessment and Reliability of Transport Emission Models and Inventory Systems
°C - Degree Celsius
CLA - Chemi-luminescence Analyser
CO - Carbon monoxide
CO_2 - Carbon dioxide
CVS - Constant Volume Sampler
DG ENTR - Directorate General Enterprise and Industry
DPF - Diesel Particle Filter
ECE - United Nations Economic Commission for Europe
ECU - Engine Control Unit
EFM - Exhaust Flow Meter
e.g. - Exempli gratia, example given
EU - European Union
EUDC - Extra Urban Driving Cycle
FTP - Federal Test Procedure
g - Gram
GPS - Global Positioning System
HFID - Heated Flame Ionization Detector
i.e. - Id est, that is
JRC - Joint Research Centre
JTC - Japanese Test Cycle
Kg - Kilogram
km - Kilometre
kW - Kilowatt
m - Metre
min - Minute
MVEG - Motor Vehicle Emissions Group
NDIR - Non-Dispersive Infrared
NDUV - Non-Dispersive Ultraviolet
NEDC - New European Driving Cycle
Nm - Newton meter
NMHC - Non-methane hydrocarbons
No. - Number
NO - Nitrogen monoxide
NO_X - Nitrogen oxides
NTE - Mot-to-exceed
OCE - Off-cycle emissions
PEMS - Portable Emission Measurement Systems
PM - Particulate matter
PM_{10} - Particulate matter with an aerodynamic diameter of 10 micrometers or less
ppm - Parts per million
ppt - Parts per thousand

RPA - Relative Positive Acceleration
rpm - Repetitions per minute
s - Second
THC - Total hydrocarbons
USA - United States of America

1 Introduction

Emissions testing in the laboratory forms an essential part of the type approval procedure for light-duty vehicles within the European Union. Emissions testing follows a predefined procedure that consists of a specified driving cycle as well as prescribed test conditions at which vehicles are tested on a chassis dynamometer (EC, 2007a,2008). This approach yields verifiable and comparable data on emissions and fuel consumption and provides clear design criteria for light-duty vehicles, which have to comply with currently applicable emission limits.

Although emission limits have become increasingly stringent in the past decade, road transport remains the most important source of NO_X (nitrogen oxides) and CO (carbon monoxide) emissions by 2008, contributing 41% and 34%, respectively to the total emissions of these pollutants within the European Union (EEA, 2010). In particular, urban air pollution continues to persist at high levels, with 16% and 26% of EU's urban population being exposed to higher NO_2 (nitrogen dioxide) and PM_{10} (particulate matter of 10 micrometers or less) concentrations than specified by applicable air quality standards (EEA, 2009). Persisting air quality problems have triggered several policy responses that are targeted at emissions of light-duty vehicles:

(i) The introduction of more stringent emission limits for light-duty vehicles with Euro 5b in 2011 and Euro 6 in 2014 (EC, 2007a,2008).

(ii) The replacement of the currently applied New European Driving Cycle (NEDC) by a world-wide harmonized driving cycle in 2014 (EC, 2009a).

(iii) Potentially, the implementation of supplementary measures for verifying vehicles' emissions outside of the emissions testing with a single standardized driving cycle in 2014.

Particular concerns arise because emissions testing with the NEDC under laboratory conditions might not represent the actual on-road emissions of light-duty vehicles with sufficient accuracy. Several studies have indicated that specifically on-road NO_X emissions of light-duty diesel vehicles might substantially exceed Euro 2-4 emission limits (Pelkmans and Debal, 2006; Hausberger and Blassnegger, 2006; Vojtisek-Lom, 2009). Yet, comprehensive analysis of on-road emissions of light-duty diesel and gasoline vehicles that comply with Euro 3-5 is still unavailable.

This report addresses the existing knowledge gaps by using Portable Emission Measurement Systems (PEMS) to analyze the on-road emissions of 12 light-duty diesel and gasoline vehicles. The selected vehicles include small and midsize passenger cars as well as transporters and a minivan. The analysis contributes further to a knowledge base on real-world driving patterns within the European Union.

The results might assist the design of a road map for developing a suitable on-road emissions test procedure that could supplement the world-wide harmonized driving cycle in the European type approval of Euro 6 vehicles by 2014 (EC, 2007a). The report thereby contributes to a comprehensive EU environmental and industrial policy that assures compliance of light-duty vehicles with emission limits under normal conditions of use.

This report continues by presenting principal background information on the European emissions legislation as well as on laboratory emissions testing and PEMS (Section 2). Afterwards, Section 3 presents the research methodology and Section 4 provides the results of the PEMS analyses. The report finishes with a discussion (Section 5) and conclusions (Section 6).

2 Background

This section sets the stage for the later analyses by presenting information on (i) the status of emission legislation within the European Union with respect to light-duty vehicles, (ii) the official procedure to test emissions of light-duty vehicles, and (iii) the current developments in the on-road emissions testing with PEMS.

2.1 The current status of European light-duty vehicle emissions legislation

Emissions testing as part of the type approval procedure for light-duty vehicles is regulated within the European Union by the Co-decision regulation No. 715/2007 of 20 June 2007 (EC, 2007a) and the Comitology regulation No. 692/2008 of 18 July 2008 (EC, 2008). These regulations refer to vehicles of:

- (i) categories M1 and M2 - passenger vehicles comprising no more than eight seats in addition to the driver's seat and having a maximum mass not exceeding 5 tonnes
- (ii) categories N1 and N2 - vehicles used for the carriage of goods and having a maximum mass not exceeding 12 tonnes

Vehicles of these categories currently have to comply, with the exception of a few vehicle types used for special purposes, with Euro 5 emission limits of the following pollutants (Table 1):

- (i) total hydro carbons (THC)
- (ii) non-methane hydro carbons (NMHC)
- (iii) nitrogen oxides (NO_X)
- (iv) carbon monoxide (CO)
- (v) particulate matter (PM) in the case of diesel engines and gasoline direct injection engines

The European emission legislation includes additional provisions, such as requirements for low temperature emission tests at -7°C for gasoline vehicles, which have to comply with limits of 15 g/km for CO and 1.8 g/km for HC, measured over the urban part of the NEDC (EC, 2001). Carbon dioxide emissions are currently unrestricted at the level of individual vehicles. The European Commission, however, defines a target for the fleet-average CO_2 emissions of new passenger cars of 130 g CO_2/km for a reverence car mass of 1372 kg (EC, 2009a).

Table 1: Currently applicable Euro 5 emission limits for light-duty vehicles of category M1 (EC, 2007a)

Pollutant	Emission limits for vehicles with spark ignition engines in mg/km	Emission limits for vehicles with compression ignition engines in mg/km
THC	100	-
NMHC	68	-
NO_X	60	180
$HC+NO_X$	-	230
CO	1000	500
PM	5.0/4.5[1]	5.0/4.5[1]

- not regulated

[1] The emission limit of 5.0 mg/km refers to Euro 5a, which is relevant for category M1 vehicles since September 2009. The emission limit of 4.5 mg/km refers to Euro 5b, which will be relevant for category M1 vehicles from January 2011 onwards.

In view of the introduction of more stringent Euro 6 emission limits in 2014, Regulation 715/2007 (EC, 2007a) contains provisions that should assure compliance of vehicles with applicable emission limits during both type approval and on-road driving under normal conditions of use[1]:

(i) Recital (15) requests the Commission to investigate the use of PEMS and so-called *not-to-exceed* regulatory concepts in the context of the revision of the NEDC.

(ii) Article 4(2) requires that manufacturer ensure an effective limitation of emissions pursuant to this Regulation, throughout the normal life of the vehicles under normal conditions of use.

(iii) Article 5(2) in conjunction with the definition in Article 3(10) prohibits the use of defeat devices under conditions that are likely to occur during normal vehicle operation, if these conditions are not substantially included in the test procedures for verifying emissions[2].

(iv) Article 14(3) requires the European Commission to keep reviewing procedures, tests, and requirements used to measure emissions. If reviews identify that provisions are no longer adequate or, in particular, do not reflect on-road emissions from real-world driving, the provisions should be adapted accordingly through the Comitology procedure.

The compliance of light-duty vehicles with applicable emission limits is verified by emissions testing on the chassis dynamometer in the laboratory. The next section describes in greater detail the key characteristics of the driving cycle, i.e., the NEDC that is currently used for standard laboratory emission tests within the European Union.

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[1] Normal conditions of use might also include particularly polluting driving pattern such as driving at very high speeds, as it is frequently observed on the German autobahn, engine cold start at very low temperatures, or idling in congested traffic that may cause a cool down of after-treatment devices.

[2] Defeat devices are elements of design that sensor certain ambient and vehicle parameters for the purpose of influencing the operation of any part of the emission control systems, resulting in a reduced effectiveness of emission control technologies.

2.2 The test procedure for light-duty vehicle emissions within the EU

Emissions testing as part of the type-approval process for light-duty vehicles has to balance two criteria:

(i) quantifying as far as possible vehicle emissions under real-world driving conditions
(ii) assuring reproducibility and comparability of emission measurements

The testing of emissions and fuel consumption of light-duty vehicles takes place in the laboratory on chassis dynamometers. The details of the test procedure are described by Directive 98/69/EC (EC, 1998) and its further amendments.

Before the emissions test, vehicles have to soak for at least 6 hours at a test temperature of 20-30°C. Emissions are then measured while vehicles follow the speed profile of the New European Driving Cycle (NEDC). The entire NEDC consists of four repeated ECE-15 driving cycles of 195s duration each and one extra-urban driving cycle (EUDC) of 400s duration (Figure 1).

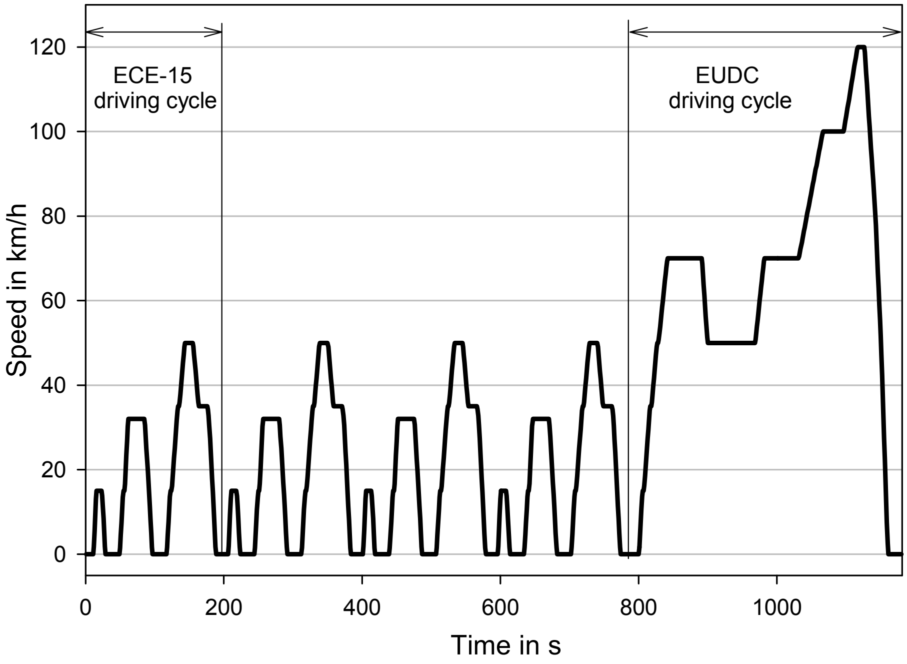

Figure 1: Speed profile of the New European Driving Cycle (NEDC)

The four ECE-15 cycles represent urban driving conditions that are characterized by low vehicle speed, low engine load, and low exhaust gas temperature. By contrast, the EUDC in the second part of the NEDC accounts for extra-urban and high speed driving modes up to a maximum speed of 120 km/h. The entire NEDC covers a distance of 11,007 m in a time period of 1180 s and at an average speed of 34 km/h. An initial idling period has been eliminated in the NEDC, thus emissions sampling begins with the start of the engine. Emissions are typically sampled with a Constant Volume Sampler (CVS) and expressed as averages over the entire test cycle in grams per kilometre [g/km] for each of the regulated pollutants (see Table 1).

The main characteristics of the NEDC in comparison to other certification cycles, i.e., the US FTP-75 driving cycle and the Japanese JTC cycle as well as the ARTEMIS urban driving cycle are provided in Table 2. The NEDC was developed to assure comparability and reproducibility of vehicle emissions that have been tested at standard conditions. Such an approach to emissions testing comes inevitable with limitations regarding the ability to reproduce actual on-road emissions. Criticism of the NEDC refers in particular to its smooth acceleration profile (André and Pronello, 1997) that requires only a very narrow range of possible engine operation points (Kageson, 1998).

Table 2: Comparison the key characteristics of selected driving cycles

	NEDC	**ECE-15**	**US FTP-75**	**JTC 10-15 mode**
Region	EU	EU	USA	Japan
Trip duration [s]	1180	780	1874	660
Trip distance [km]	11.007	4.052	17.77	4.16
Average speed [km/h]	33.6	18.7	34.1	22.7
Maximum speed [km/h]	120	50	91	70
Share [%]				
- Idling	24	30	19	32
- low speed >0≤50 km/h	55	70	60	49
- medium speed >50-90 km/h	14	0	19	19
- high speed >90 km/h	7	0	2	0

Table 2 (continued): Comparison the key characteristics of selected driving cycles

	ARTEMIS urban	**ARTEMIS rural**	**ARTEMIS motorway**[1]
Region	EU	EU	EU
Trip duration [s]	920	1081	1067
Trip distance [km]	4.47	17.27	28.74 (29.55)
Average speed [km/h]	17.5	57.5	97.0 (99.7)
Maximum speed [km/h]	58	112	132 (150)
Share [%]			
- Idling	29	3	2 (2)
- low speed >0≤50 km/h	69	31	15 (15)
- medium speed >50-90 km/h	2	59	13 (13)
- high speed >90 km/h	0	7	70 (70)

[1] Values in parentheses indicate the 150 km/h specification of the ARTEMIS motorway driving cycle.

The NEDC only insufficiently represents on-road driving pattern that are characterized by low speed and high torque operation, steep and dynamic transient velocities, and driving at very high-speed. It is hence likely that vehicles comply with applicable emission limits during NEDC testing although they might show substantially higher pollutant emission levels alongside with elevated fuel consumption and CO_2 emissions on the road (André, 1996; Hausberger and Blassnegger, 2006; Pelkmans and Debal, 2006; Tzirakis et al., 2006). These limitations have been acknowledged by the European Commission and triggered the current research activities around the implementation of Euro 6 by 2014, including the development of (i) a more representative and internationally harmonized driving cycle as well as (ii) a supplemental off-cycle emissions test procedure for assessing the on-road emissions of light-duty vehicles for type approval (EC, 2009c).

2.3 Current developments in on-road emissions testing with PEMS

On-road emissions testing with PEMS has been so far mainly developed to evaluate the in-service conformity of EURO V and EURO VI engines of heavy-duty vehicles (EUR, 2006a,b,c; Bonnel and Kubelt, 2010). Emissions testing of heavy-duty vehicles as part of the type approval procedure is specified by Regulation (EC) No. 595/2009 of the European Parliament and of the Council (EC, 2009b). This regulation defines rules for the in-service conformity of vehicles and the durability of emission control devices. In particular, EC (2009b) suggests (i) considering the application of portable emission measurement systems (PEMS) for verifying the in-service conformity of heavy-duty vehicles and (ii) introducing supplemental procedures to control on-road (so-called *off-cycle*) emissions.

Verifying the in-service conformity of heavy-duty vehicles typically requires to remove the engine from the vehicle and to test its emissions in dedicated engine test cells. Such an approach is, however, very impractical and expensive. Therefore, it has been proposed to develop a protocol for in-service conformity checking of heavy-duty vehicles based on PEMS. The European Commission (DG ENTR in co-operation with DG JRC) launched in January 2004 a co-operative research programme to study PEMS applications for heavy-duty vehicles within the European Union. The experimental activities started in August 2004 and resulted in a successful application of PEMS to heavy-duty vehicles (Bonnel and Kubelt, 2010). Following the success of the EU-PEMS project, the European Commission announced the intention to launch a manufacturer-run pilot programme at the 97th Motor Vehicle Emissions Group (MVEG) Meeting on 1 December 2005. The main purpose of the programme was to evaluate the PEMS-based technical and administrative procedures for a larger range of technologies and in statistically more significant numbers. The PEMS pilot programme was started in autumn 2006; the outcome of the programme is expected to provide further insight on the potentials to introduce in-service conformity provisions based on PEMS in the European type-approval legislation for heavy-duty vehicles.

Based on their successful application to heavy-duty vehicles, PEMS might potentially also be applicable to light-duty vehicles as supplemental measure to ensure that vehicle emissions are appropriately controlled outside standardized laboratory conditions (EC, 2007a). The JRC initiated a first PEMS test campaign to obtain insights into the suitability of PEMS for emissions testing of Euro 3-4 light-duty vehicles in 2007 based on an Administrative Arrangement with DG ENTR (EC, 2007c). The PEMS testing of Euro 5 vehicles in 2009 and 2010 was then commissioned by the recent Administrative Arrangement No. SI2.552273 between the JRC and DG ENTR (EC, 2009c). The aim of this Administrative Arrangement was in particular to obtain on-road emission values for a range of Euro 5 vehicles and thereby supporting the development of suitable off-cycle emission test procedures that might supplement the standard laboratory emission test of Euro 6 vehicles from 2014 onward. The results of both test campaigns are documented in the present report, which continues in the next section by explaining in greater detail the methodology used for the PEMS test campaign of light-duty vehicles.

3 Methodology

The methodology section contains four parts: the first part provides an overview of test vehicles; the second part presents the routes used for PEMS testing; the third part explains PEMS equipment and test protocol; the fourth part explains data processing and data analysis.

3.1 Test vehicles

The analysis presented in this report includes passenger cars, i.e., vehicles of category M1, for which the currently applicable emission limits are provided in Table 1. The PEMS test fleet consists of 12 light-duty vehicles, comprising 5 gasoline vehicles, 1 gasoline-hybrid vehicle, and 6 diesel vehicles. Nine vehicles represent small and compact passenger cars, one vehicle is a minivan, and two vehicles represent small transporters. All test vehicles belong to category M1 of the European type approval classification (EC, 2007b), are sold on the European market, and passed type approval based on Euro 3-5 emission limits (Table 3). The second phase of the PEMS test campaign in the years 2009 and 2010 focused in particular on Euro 5 vehicles with the aim of complementing the data generated for Euro 3 and Euro 4 vehicles during the first project phase between 2007 and 2008.

3.2 PEMS test routes

The PEMS test campaign started with the testing of Vehicles A and C on local routes, including trips from Ispra to Milan as well as in down-town Milan. Based on the results of these tests, four defined routes were developed (Table 4, Figure 2), which later served as standard test routes for all subsequent PEMS tests of Vehicles B and D-L. The characteristics of these four test routes reflect as far as possible the diversity of normal on-road driving in Europe and include:

(i) Route 1: Ispra-Milan-Ispra; representing a mix of rural and motorway driving
(ii) Route 2: Ispra-Varese-Ispra; representing a mix of rural and urban driving
(iii) Route 3: Ispra-Sacro Monte-Ispra; representing a mix of rural and severe uphill-downhill driving with an elevation difference of around 800 m
(iv) Route 4: Motorway; representing high-speed driving at speeds of up to 130 km/h

Figures 3 and 4 provide an overview of altitude profiles and the typical speed distributions of the four test routes.

Table 3: Specifications of test vehicles

Vehicle	Vehicle category	Model year	Mileage at test start [km]	Fuel	Engine capacity [ccm]	Maximum engine power [kW]	Mass of CO_2 emitted during standard NEDC testing [g/km] / [cumulative kg]	Emission treatment technology	Applicable emission limit
A	N1 (small transporter)	2007	20,743	diesel	1997	69	182 / 2.00	oxidation catalyst, no DPF	Euro 3, Class II
B	M1 (minivan)	2007	13,831	gasoline	1798	88	169 / 1.86	3-way catalyst	Euro 3
C	N1 (small transporter)	2007/8	~20,000	diesel	2461	96	218 / 2.40	oxidation catalyst, no DPF	Euro 4, Class II
D	M1 (small passenger car)	2007	~800	diesel	1461	50	120 / 1.32	oxidation catalyst, no DPF	Euro 4
E	M1 (compact passenger car)	2004	~100,000	diesel	1896	77	140 / 1.54	oxidation catalyst; no DPF	Euro 4
F	M1 (small passenger car)	2007	16,996	gasoline	1149	55	139 / 1.53	3-way catalyst	Euro 4
G	M1 (compact passenger car)	2007	1,023	gasoline-hybrid	1497	57[*]	104 / 1.14	3-way catalyst	Euro 4
H	M1 (compact passenger car)	2009	3,408	diesel	1598	88	129 / 1.42	oxidation catalyst, DPF	Euro 5
I	M1 (compact passenger car)	2009	4,667	diesel	1995	130	128 / 1.41	oxidation catalyst, DPF	Euro 5
J	M1 (compact passenger car)	2009	~5,000	gasoline	1595	75	166 / 1.83	3-way catalyst	Euro 5
K	M1 (small passenger car)	2009	-10,000	gasoline	1242	51	119 / 1.31	3-way catalyst	Euro 5
L	M1 (small passenger car)	2010	1,909	gasoline	1242	44	127 / 1.40	3-way catalyst	Euro 5

[1] gasoline engine only

Table 4: Characteristics of PEMS test routes

Test route	Section	Distance [km]	Typical average speed [km/h]
Route 1	rural	35	50
	motorway	100	90
	Total	**135**	**65**
Route 2	rural	51	40
	urban	10	25
	Total	**61**	**35**
Route 3	rural	50	45
	uphill-downhill	10	30
	Total	**60**	**40**
Route 4	rural	37	39
	motorway	95	108
	Total	**132**	**71**

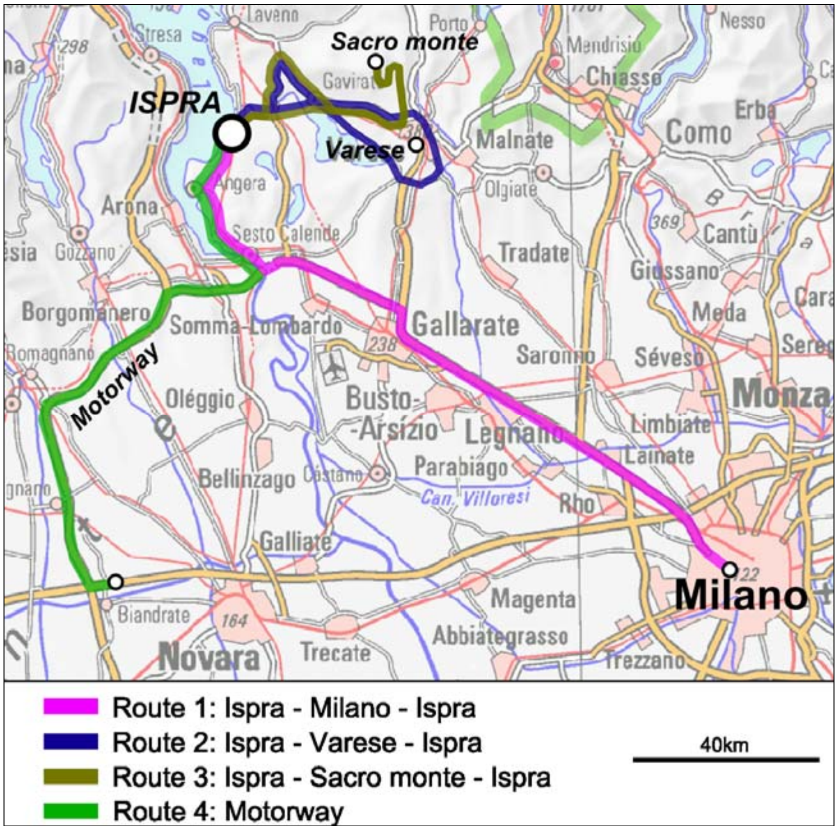

Figure 2: Topographic map of the PEMS test routes

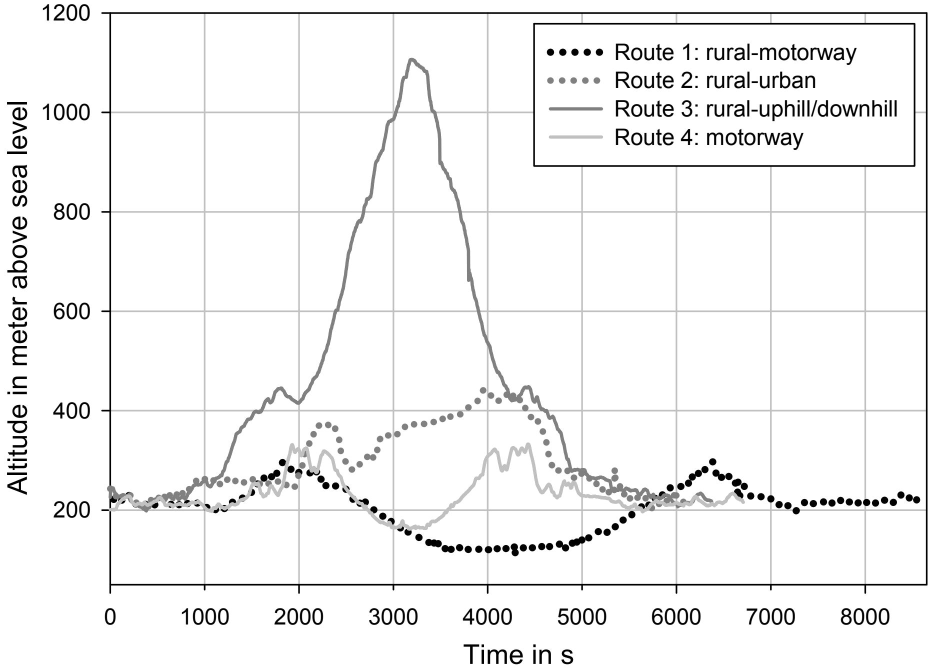

Figure 3: Altitude profiles of PEMS test routes; NEDC testing, by comparison, does not include any altitude changes

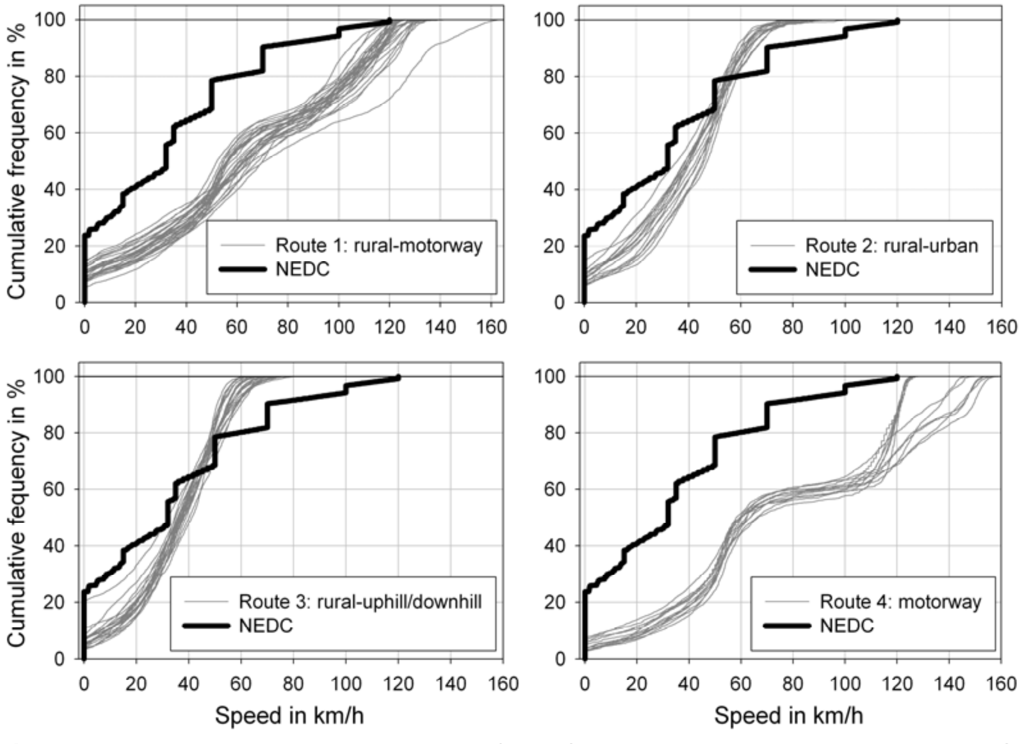

Figure 4: Typical speed distributions of PEMS test routes in comparison to the NEDC

The four test routes represent different on-road driving pattern, which can also be characterized by plotting the relative positive acceleration (RPA) as function of vehicle speed. The RPA is calculated as the integral of the product of instantaneous speed and instantaneous positive acceleration over a defined section of the test route, a so-called sub-trip, such as:

$$RPA = \frac{\int_{0}^{t_j} (v_i \times a_i)dt}{x_j} \qquad (\textit{Equation 1})$$

where: t_j = time
x_j = distance of sub-trip *j*
v_i = speed during each increment *i*
a_i = instantaneous positive acceleration during each increment *i* contained in the sub-trip *j*

A sub-trip is defined here as any part of the test route, in which the vehicle speed is at least 2 km/h for a period of at least 5 seconds. Individual sup-trips are separated from each other by periods of idling or very slow motion in congested traffic. The length and number of sub-trips contained in a PEMS test depends on the route characteristics and the traffic situation and might show substantial variability both between and within individual test routes. Thus, sub-trips may differ substantially in their length. The maximum achievable RPA is directly related the vehicle power. Additional factors affecting the magnitude and distribution of RPA values such as: (i) the drivers' behaviour and driving style, (ii) climatic and ambient conditions, as well as (iii) traffic and road conditions. The distribution of RPA values allows comparing the characteristics of different routes and may be used as criterion to standardize on-road PEMS emissions testing.

The RPA values of the individual PEMS test routes show distinct pattern that differ from the ones of the NEDC (Figure 5). In particular Routes 1 and 4 include a larger share of high-speed driving than the NEDC. Vehicle testing on the four test routes covers furthermore a substantially larger range of the RPA-speed spectrum than does the conventional NEDC testing. Low RPA values in the range of 0.1-0.4 m/s^2 at velocities of 0-50 km/h represent the majority of driving conditions on our four PEMS test routes. Still extreme conditions exist such as RPA values above 1 m/s^2 at low speeds or relatively low RPA at high speeds in the range of 120-130 km/h occur; these driving conditions are not covered by the NEDC.

Overall, Route 1 with a mix of rural and motorway driving seem to capture best the potentially large variability of on-road driving conditions. Still, driving on identical routes can lead to considerable variability in the RPA-speed trace depending on vehicle type as well as road and traffic conditions. The overview in Figure 5 clearly indicates the shortcomings of the NEDC: it completely excludes driving at low velocities and medium too high acceleration (RPA >0.2 m/s2) as well as at high velocities and low acceleration. The ongoing development of a world-wide harmonized driving cycle addresses parts these shortcomings; the new driving cycle well be implemented in the European Union by 2014 with the introduction of Euro 6 emission limits.

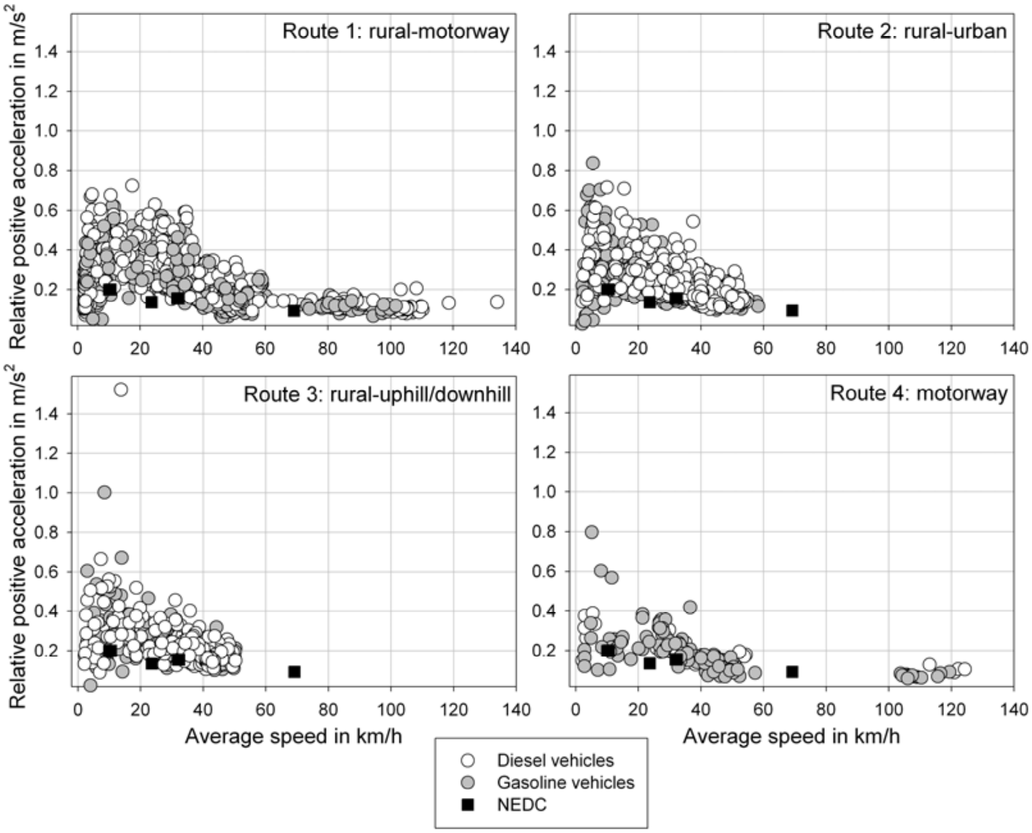

Figure 5: The relative positive acceleration of sub-trips composing the four PEMS test routes and the NEDC

Regardless, also the driving on the four PEMS test routs has one particular limitation: It is not able to reproduce driving at very high speeds (i.e., >140 km/h) as it frequently occurs on the German Autobahn. This limitation is relevant because Germany presents the largest vehicle market in Europe and operates an Autobahn network of more than 12,000 km, which accounts for one third of all vehicle-kilometres driven in Germany. Large parts of the Autobahn are free of a speed limit. In 1995, the average vehicle speed on the Autobahn was 134 km/h (Pander, 2007) and thereby higher than the speed limit enforced in all other European countries[3].

3.3 PEMS equipment and test protocol

For the emissions testing of light-duty vehicles, a Semtech-DS PEMS from Sensors Inc. was used. This equipment is commercially available and consists of a tail-pipe attachment, heated exhaust lines, a Pitot tube for measuring the exhaust mass flow and temperature, exhaust gas analyzers, a data logger to the vehicle network, a GPS, sensors for ambient temperature and humidity, and exhaust pipelines (Figure 6). The mass of the PEMS systems including an external battery for power supply amounts to 80 kg and is thereby equivalent to the mass of a passenger. PEMS accounts at maximum for 9% of the mass of tested vehicles. Although the mass of the PEMS equipment might not substantially affect the test results, it may introduce a bias into the emission measurements. This bias may, however, allow reproducing on-road emissions of with more than one person in the vehicle.

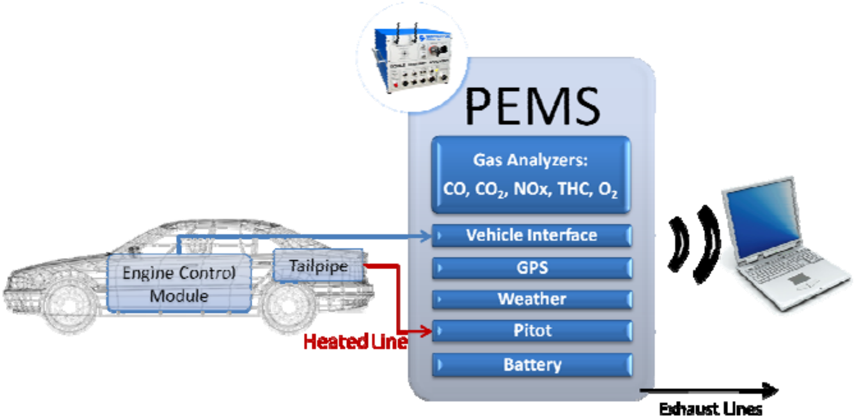

Figure 6: Schematic overview of PEMS and auxiliary components (courtesy Sensors Inc.)

PEMS measures the exhaust gas concentrations of the regulated pollutants THC, CO, and NO_X, as well as of CO_2 and NO emissions, the exhaust mass flow and the exhaust temperature. The complete set of parameters measured with PEMS during on-road emission tests, as well as the corresponding measurement technique, is provided in Table 5. Total hydrocarbon emissions are measured by a heat flame ionization detector (HFID); CO and CO_2 emissions are measured by a non-dispersive infrared (NDIR) analyzer; NO and NO_2 emissions are measured by a non-dispersive ultraviolet (NDUV) analyzer; the total NO_X emissions are then calculated from the NO and NO_2 data. Particulate matter (PM) is excluded from this analysis.

Table 5: Overview of parameters measured with PEMS

Category	Parameter	Measurement technique
Exhaust gas pollutants	THC	HFID
	CO	NDIR analyzer
	CO_2	NDIR analyzer
	NO and NO_2	NDUV analyzer
	Exhaust flow rate	EFM
	Exhaust temperature	EFM temperature sensor
Vehicle characteristics	Vehicle speed	GPS
	Vehicle position and altitude	GPS
	Acceleration	GPS
	Distance travelled	GPS
Ambient conditions	Elevation	GPS
	Ambient humidity	Humidity sensor
	Ambient temperature	Temperature sensor
	Ambient pressure	Pressure sensor

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[3] Italy and Poland present exceptions: The speed limit on three-lane (six lanes in two directions) highways in Italy may be 150 km/h if indicated. The speed limit on highways in Poland will be 140 km/h from 2011 onward.

To measure the exhaust mass flow and exhaust temperature, the Semtech-DS uses an exhaust mass flow meter (EFM) equipped with differential pressure devices and thermocouples. The EFM has an accuracy of at least ± 3.0% at a resolution of 0.003 m^3/min and an exhaust temperature range from ambient to 550 ºC. The random error of PEMS measurements typically accounts for 2-3% of the measured value. The accuracy of PEMS has been verified against laboratory equipment by Rubino et al. (2007a). The verification tests were conducted on a 48 inches chassis dynamometer (MAHA; maximum power 150 kW; maximum velocity 200 km/h; inertia of 454-4500 kg) over the NEDC driving cycle. A Horiba MEXA-7400HTR-LE was used as reference for measuring NO_X, CO, HC, and CO_2 emissions. The NO_X emissions were measured using a chemiluminescence analyser (CLA; the total hydrocarbons emissions were measured by a heated flame ionization detector (HFID), CO and CO_2 were determined by NDIR analyzers. The CVS flow rate was set at 6 m^3/min. The gaseous emissions were measured during the emission tests according to the current European type-approval protocol. Good agreement was found between the emissions as measured with PEMS and the reference test cell analyzers (Horiba) as shown in Figure 7 (see also EPA, 2008; Rubino et al., 2007a,b). The deviations between both PEMS and laboratory equipment are negligible with respect to the findings of this report.

The test protocol of the Semtech-DS PEMS for measuring on-road emissions of light-duty vehicles was adapted in two points from the one developed for heavy-duty vehicles (EUR, 2006c):

(i) The emissions were measured directly from cold start, including cranking.
(ii) The vehicle conditioning (e.g., the vehicle temperature) was monitored before, during, and after the test.

The main components of the Semtech-DS PEMS (i.e., pumps, electronic equipment, and analysers) were installed in the cabin of the vehicle, which avoids contamination, excessive vibrations, and heating of the equipment. The exhaust mass flow meters were attached to the vehicle's tailpipe; GPS and weather station were installed outside of the vehicle (Figure 8). The power for the analytical equipment was supplied by an external battery. This reduces the interference of PEMS with the engine operation and allows PEMS testing for up to 2.5 hours; the battery, nevertheless, introduces additional weight to the PEMS equipment. PEMS has been proven to yield reliable emission measurements in previous test campaigns for heavy-duty and light-duty vehicles (EUR, 2006a,b; Rubino et al., 2007a; Bonnel and Kubelt, 2010).

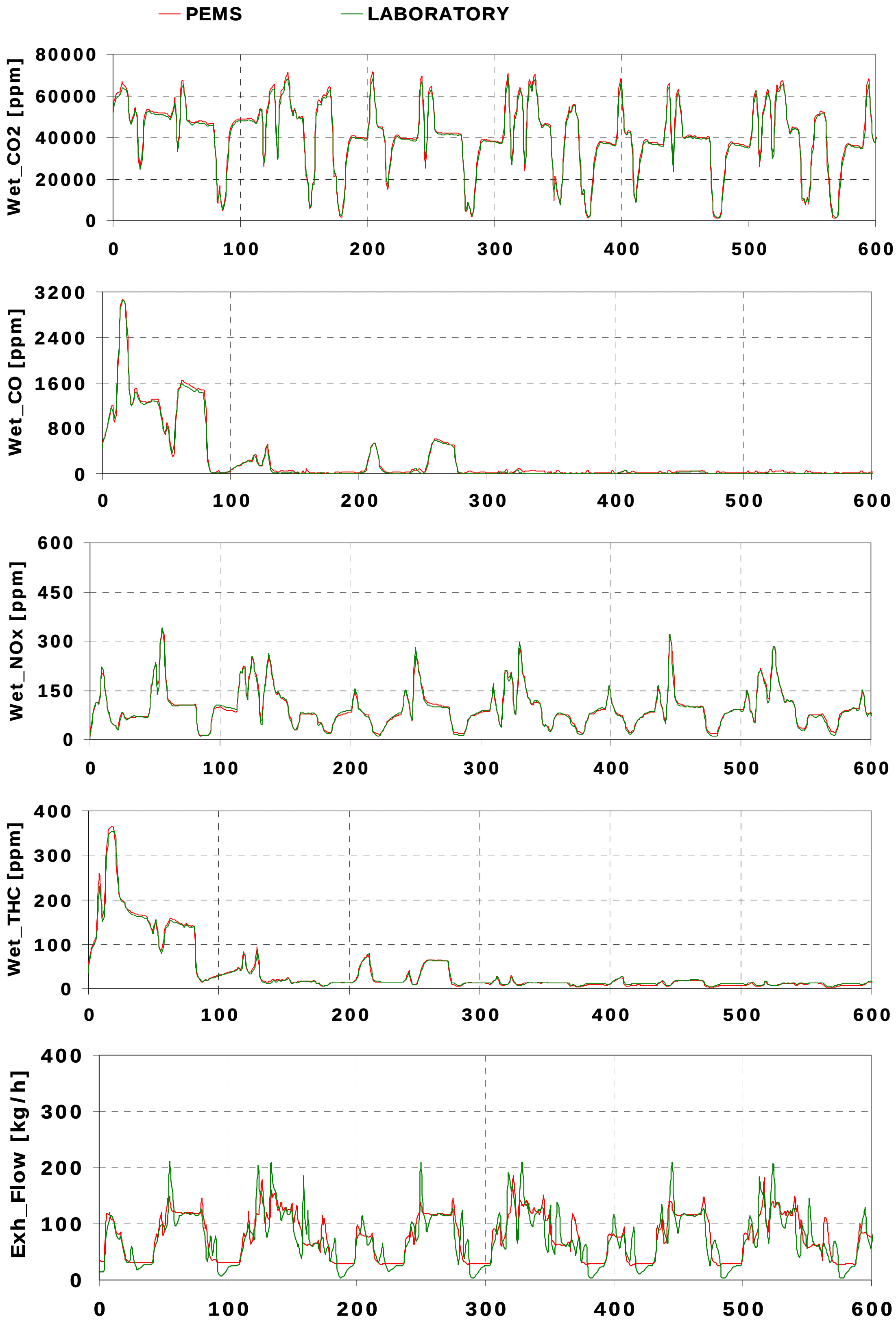

Figure 7: Comparison of emissions as measured with PEMS and standard laboratory equipment

(i) EFM

(ii) PEMS installation

(iii) PEMS main unit

(iv) external battery

Figure 8: Demonstrating the installation of PEMS in a light-duty vehicle

3.4 Data collection and analysis

3.4.1 Complementary data supply and emission tests

In addition to PEMS testing, the emissions of Vehicles A, D, and G-L were determined based on NEDC testing in the laboratory. All laboratory tests were conducted on a 48 inches (118 cm) chassis dynamometer produced by MAHA. A Horiba MEXA-7400HTR-LE was used as standard laboratory equipment for measuring THC, CO, HC, NO_X, and CO_2 emissions (see also Section 3.3). The vehicles that were tested based on the NEDC generally complied in the laboratory with the applicable emission limits.

For Vehicles B, C, E, and F no such NEDC tests were performed because in the early phase of the PEMS test campaign attention was predominantly paid on the reliability and completeness of PEMS measurements, rather than on establishing on-road emission values of light-duty vehicles in comparison to laboratory tests. The PEMS tests of the various vehicles were complemented as far as possible by vehicle data such as engine fuel rate [g/s], engine speed [rpm], or engine torque [Nm] obtained from the Engine Control Unit (ECU) via a data logger.

3.4.2 Data analysis

During the actual PEMS testing, each vehicle started from the JRC in Ispra (Italy) and returned to the JRC for technical checks, calibration, and data download. PEMS measures emissions with a time resolution of one second. Recorded emissions data were uploaded together with data from the PEMS's GPS system into EMROAD©, which is an Excel® tool developed by the JRC for analyzing and evaluating PEMS data (Kubelt and Bonnel, 2007). PEMS records uniformly NO_X emissions, which are uncorrected for ambient humidity and intake air temperature. This approach is justified by the aim of this project, i.e., to report on-road emissions as they occur under real-world driving conditions.

EMROAD© calculates first average emissions for the entire test route, expressed as grams per kilometre. EMROAD© also presents emissions in alternative metrics, e.g., as function of time or emitted CO_2 mass. These metrics will, however, not be discussed in detail because emission limits for light-duty vehicles are uniformly defined by EU legislation as distance-specific values in grams per kilometre (EC, 2007a).

To enable a more detailed analysis of emissions, EMROAD© allows calculating emission averages for individual averaging windows that represent sub-trips of a test route. This method is generally referred to as the averaging window method and represents an established methodology that will be used for the official emissions testing and characterization of Euro VI heavy-duty vehicles (EC, 2010). The method reduces fluctuations in the second-by-second emissions data and enables a more detailed understanding of emission variability in comparison to route averages. The principle approach is as follows: Pollutant emissions are averaged over intervals of a predefined duration. These intervals are referred to here as *averaging windows*. The duration of an averaging window is determined in the case of heavy-duty vehicles by a predefined quantity of work the vehicle's engine has performed until a certain point. This reference metrics is chosen because emission limits for heavy-duty vehicles are defined as work-specific quantities. In the case of heavy-duty vehicles both work-based averaging windows and applicable emission limits are therefore directly linked to an actual engine parameter (Kubelt and Bonnel, 2007; Bonnel and Kubelt, 2010; EC, 2010). In the case of light-duty vehicles emission limits are defined as distance-specific values (see Table 1). In line with the definition of emission limits (EC, 2007a), we chose in this report the distance travelled by the vehicle [km] as reference parameter to determine the length of an averaging window[4]. To make reference to the NEDC laboratory testing, the duration of a window is determined precisely as the distance travelled until the vehicle has emitted a cumulative mass of CO_2 that is equivalent to the CO_2 mass emitted during NEDC testing (see Table 3, column 8 from the left; Figures 9 and 10). This approach assures comparability of the distance-specific averaging window emissions with the Euro 3-5 emission limits. It is important to note that the CO_2 mass emitted presents a constant but the distance travelled by the vehicle may vary depending on the actual driving conditions. The averaging windows move at time increments equal to the data sampling period, i.e., one second. The distance *d* travelled during any averaging window is determined by:

$s = s_2 - s_1$, when (*Equation 2*)

$$m_{CO_2}(d_2 - \Delta s) - m_{CO_2}(s_1) < m_{CO_2,ref} \leq m_{CO_2}(s_2) - m_{CO_2}(s_1) \qquad (\textit{Equation 3})$$

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[4] The duration of averaging windows is generally longer than the one of sub-trips (see Section 3.2). On exception presents motorway driving, which typically is not interrupted by vehicle stops. Under such conditions, sub-trips might be extremely long, thus exceeding the length of an averaging window by several factors.

where: $m_{CO_2,ref}$ = total reference CO_2 mass [kg] determined during the NEDC test

$m_{CO_2}(s_1)$; $m_{CO_2}(s_2)$ = total CO_2 mass [kg] emitted until distance s_1 and s_2

Δs = distance travelled during the time increment of the sampling period of one second (Figure 10)

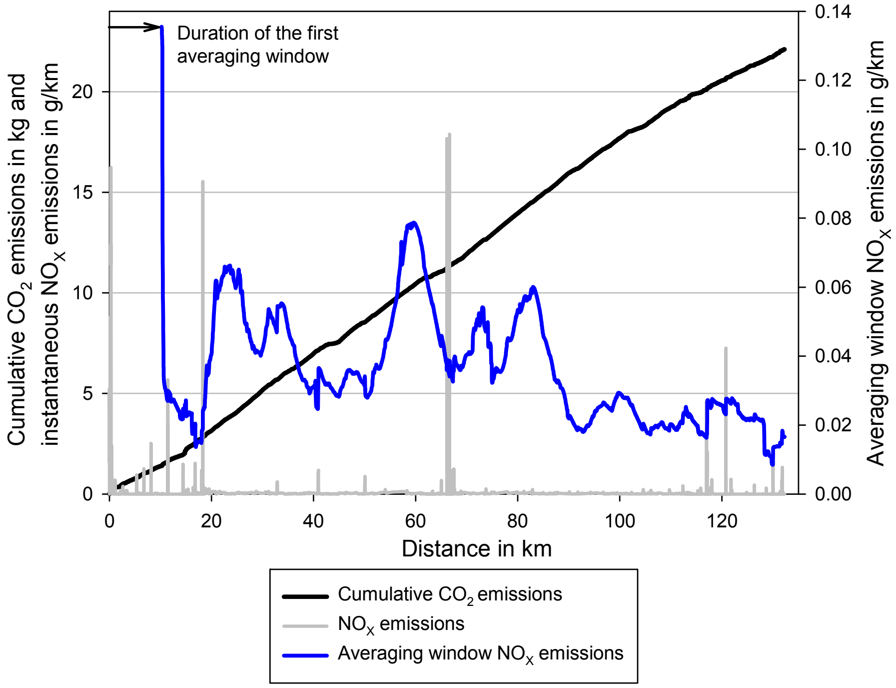


Figure 9: Example of the averaging window method for NO_X emissions; the first average is calculated once the vehicle has travelled a distance at which it has emitted a cumulative mass of CO_2 equivalent to the cumulative CO_2 mass emitted during a standard NEDC test; all consecutive windows move in increments of the sampling period, i.e., one second assuring that the cumulative CO_2 emissions match the reference CO_2 mass

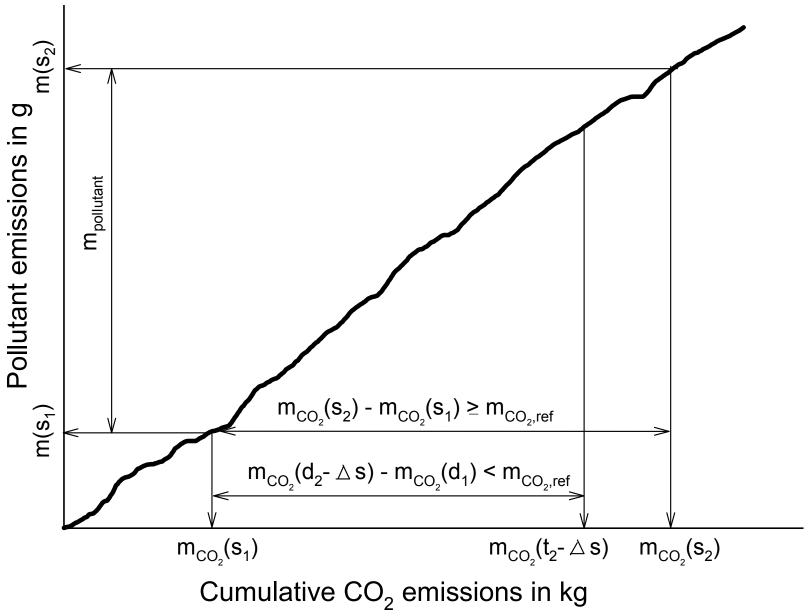


Figure 10: Schematic overview of the procedure to determine the duration of an averaging window with the CO_2 mass-based method

The CO_2 mass is calculated per window by integrating, i.e., adding the instantaneous CO_2 emissions measured with PEMS. In order to obtain a sufficient amount of data that can be used for analysis, a vehicle should emit during PEMS on-road testing at least a cumulative CO_2 mass that is equal to the cumulative CO_2 mass emitted during NEDC testing. For example, the first averaging window for Vehicle A (see Table 3) ends at a distance at which the vehicle has emitted cumulative CO_2 emissions of 2.00 kg; likewise, the averaging window for vehicle B (see Table 3) covers a distance equivalent to the cumulative CO_2 emissions of 1.86 kg. The averaging window method generally takes all measurements into account, thereby smoothing emissions data and reducing the interference of measurement spikes.

The applied averaging window method implies a peculiarity that deserves attention: The averaging window method gives unequal weight to emissions data because individual data points have different probabilities of belonging to a certain window. In particular emissions data obtained in the middle of a test procedure might be part of multiple windows where as emissions data in the beginning or at the end of an emissions test might be part of only one or a few averaging windows. This shortcoming is relevant for cold start emissions that are contained only in a few averaging windows, thus being underrepresented in the sample of averaging window emissions. We consider this problem minor with respect to the general findings of this report, in particular because cold-start emissions are specifically addressed in a separate section.

In line with Euro 3-5 emission limits, this report presents emissions uniformly in grams of per kilometre [g/km]. The presented uncertainty intervals for the route-specific average emissions indicate the maximum emissions measured over an entire test route. This approach is justified because for future emissions legislation it may be most relevant to obtain insight into the maximum level of emissions that might occur during on-road driving rather than into the overall variability of on-road emissions.

Next to presenting distance-specific emissions, also dimensionless deviation ratios (DR) are calculated. Deviation ratios present an indicator for the deviation between actual on-road emissions and the Euro 3-5 emission limits. The deviation ratio for each individual averaging window and each individual pollutant is defined as:

$$DR = \frac{DR_I}{DR_C} \qquad (\textit{Equation 4})$$

where DR_I = in-use deviation ratio
DR_C = certification deviation ratio

Both parameters are defined as:

$$DR_I = \frac{m}{s(t_2) - s(t_1)} \qquad (\textit{Equation 5})$$

$$DR_C = \frac{m_L}{s_{NEDC}} \qquad (\textit{Equation 6})$$

where: m = the mass of the respective pollutant emitted during one averaging window [g/window]

$s(t_2)$-$s(t_1)$ = the actual distance travelled by the vehicle during each individual averaging window [km/window]

m_L = the mass of the respective pollutant emitted during one NEDC driving cycle according to the Euro 3-5 emission limits [g]

s_{NEDC} = the reference distance of the NEDC driving cycle, i.e., 11.007 km

The reference pollutant mass of m_L differs depending on the applicable emission limit. The deviation ratios are calculated by using the travel distance as reference because emission limits for light-duty vehicles are defined as distance-specific values. The deviation ratios therefore differ from the so-called conformity factors that are used to characterize on-road emissions of heavy-duty vehicles by using engine work as reference quantity. The differences between both indicators and potential impacts on our results are discussed in Section 5.1.

To analyze the emission performance of vehicles under cold-start conditions, emissions during the first 300 seconds of each PEMS test were analyzed separately. During the cold start period, the various test routes differ in their characteristics only marginally from each other. Therefore, individual test routes were not differentiated. Instead average and maximum cold start emissions were calculated by combining the cold start sections of all test routes. The report continues with presenting the results of the on-road emissions testing with PEMS.

4 Results

This section presents the results of the PEMS test campaign for 12 gasoline and diesel vehicles that comply with Euro 3-5 emission limits. Special attention is paid to on-road emissions of Euro 5 vehicles because these vehicles are the most modern among the test vehicles and have to comply during NEDC testing with the currently enforced emission limits. This section continues by presenting on-road emissions for each vehicle as averages over the entire test routes (Section 4.1). Based on these results, Section 4.2 focuses in greater detail on NO_X emissions of Euro 5 vehicles, addressing in particular:

(i) the on-road emissions of Euro 5 vehicles in comparison to Euro 5 emission limits
(ii) on-road emissions of Euro 5 vehicles in comparison to Euro 3 and Euro 4 vehicles

Section 4.3 presents cold start emissions, i.e., emissions occurring during the first 300 seconds of the PEMS tests.

4.1 Average on-road emissions of light-duty vehicles

This section presents average emissions of NO_X, THC, CO, and CO_2 for the various light-duty vehicles and test routes. The average emissions are presented for each pollutant with two metrics as (i) distance-specific emissions [g/km] and (ii) dimensionless deviation ratios. The variability of emissions is indicated by error bars that present the maximum emissions measured for a vehicle on the various test routes. The PEMS results on NO_X emissions in Figures 11 and 12 show that:

(i) On-road NO_X emissions of gasoline vehicles generally stay within Euro 3-5 emission limits whereas NO_X emissions of diesel vehicles substantially exceed Euro 3-5 emission limits up to a factor of 2-4 if averaged over entire test routes.
(ii) On-road NO_X emissions show a relatively small decline from Euro 3 to Euro 5 diesel vehicles. This decline is substantially smaller than the stringency of Euro 3 to Euro 5 emission limits would suggest.
(iii) PEMS results suggest that there is no decline in the on-road NO_X emissions of Euro 3 towards Euro 5 gasoline vehicles.
(iv) On-road NO_X emissions are highest during extreme uphill-downhill driving and during driving on the Motorway at high velocities. This finding might be explained by insufficient exhaust gas recirculation at high engine loads during uphill and high-speed driving as well as decreased catalyst efficiency at cold start or during cool-down while down-hill driving and idling.
(v) The error intervals indicate substantial variability in the on-road NO_X emissions even if vehicles are driven on identical routes and thus under supposedly similar load pattern and driving conditions. This finding indicates the relatively high variability of on-road vehicle operating conditions.
(vi) Several diesel vehicles fail to meet the Euro 3-5 emission limits when tested with the NEDC; this finding might be partially attributed to deviations in chassis dynamometer settings and vehicle characteristics from type approval conditions.

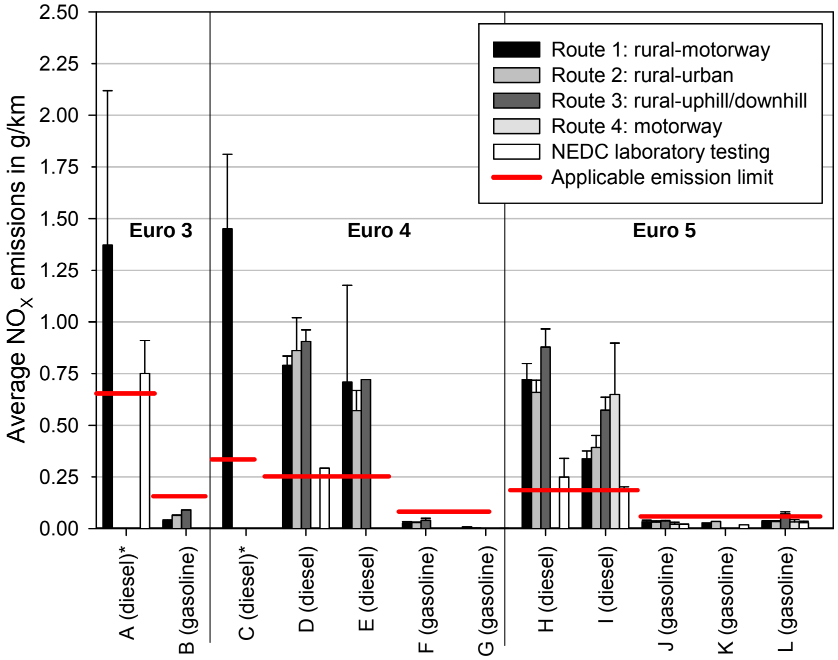


Figure 11: Average NO$_X$ emissions on the PEMS test routes and during NEDC testing in the laboratory; uncertainty intervals indicate the maximum average emissions for each test and vehicle; * Route 1: rural-motorway for Vehicles A and C (see Table 3) includes a combination of the two test routes Ispra-Milan-Ispra and Milan-urban

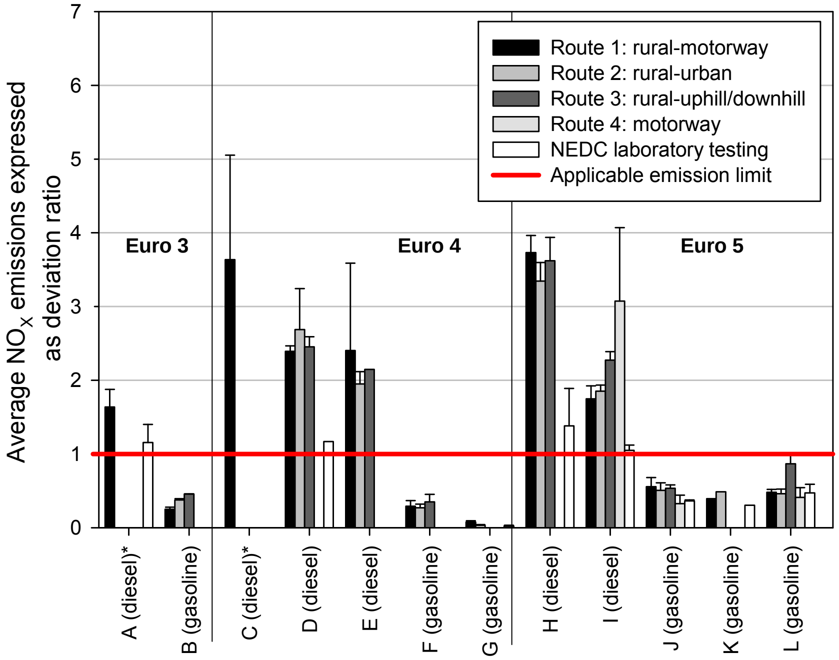


Figure 12: Average NO$_X$ emissions on the PEMS test routes and during NEDC testing in the laboratory expressed as deviation ratio; uncertainty intervals indicate the maximum average emissions for each test route and vehicle; * Route 1: rural-motorway for Vehicles A and C (see Table 3) includes a combination of the two test routes Ispra-Milan-Ispra and Milan-urban

In summary, the PEMS results indicate that the increasing stringency of Euro 3 to Euro 5 emission limits did not lead to a substantial decline in the off-cycle on-road NO$_X$ emissions of light-duty diesel vehicles. On-road NO$_X$ emissions of current Euro 5 light-duty diesel vehicles might exceed emission limits by up to a factor of four, depending on driving conditions. These results confirm earlier findings by Pelkmans and Debal (2006) and Vojtisek-Lom et al. (2009), who reported that NO_X emissions during off-cycle and on-road driving of five light-duty diesel vehicles substantially exceeded both Euro 3-4 emission limits. Overall, the results indicate that the standardized NEDC testing is clearly limited in capturing the diversity of emissions as they occur during on-road driving and may not fulfil the requirements defined by Regulation 715/2007 EC (2007a).

Of the total NO_X emissions, NO_2 is of particular interest because of its direct adverse environmental and health effects. The PEMS measurements indicate that:

(i) NO_2 emissions of gasoline vehicles are negligible in comparison to the emissions of diesel vehicles (Figures 13 and 14).

(ii) The share of NO_2 in the total NO_X emissions is substantially higher for diesel than for gasoline vehicles.

(iii) NO_2 might reach a share of up to 60% in the total NO_X emissions of diesel vehicles; the results do not allow drawing conclusions on whether this share increased from Euro 3 to Euro 5 vehicles.

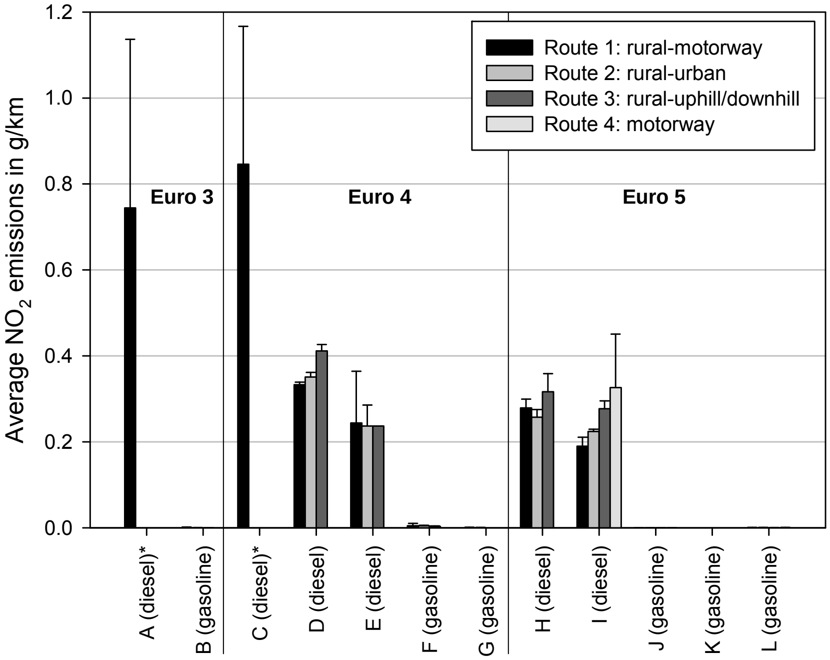


Figure 13: Average NO_2 emissions on the PEMS test routes; uncertainty intervals indicate the maximum average emissions for each test and vehicle; NO_2 was not measured during NEDC testing; * Route 1: rural-motorway for Vehicles A and C (see Table 3) includes a combination of the two test routes Ispra-Milan-Ispra and Milan-urban

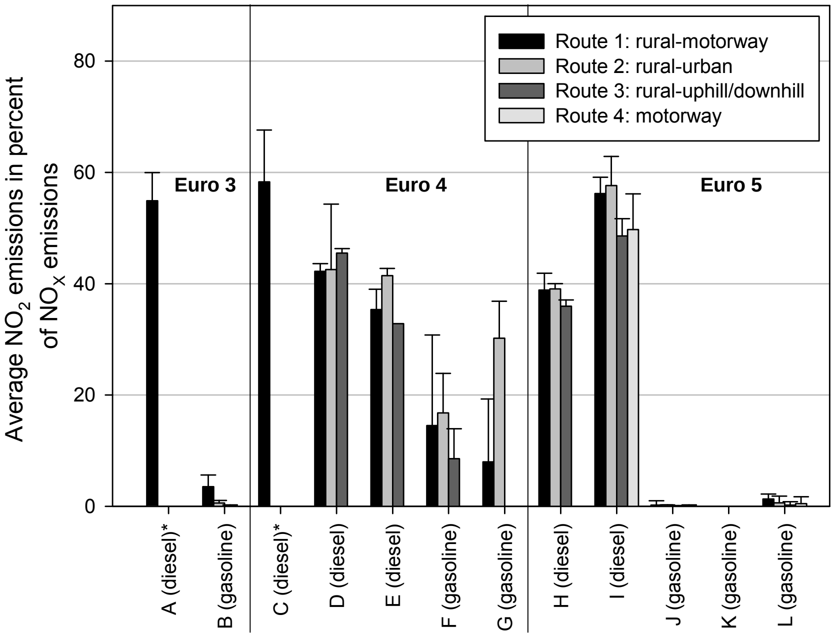


Figure 14: Average NO_2 emissions on the PEMS test routes expressed as percentage of average NO_X emissions; uncertainty intervals indicate the maximum average emissions for each test and vehicle; NO_2 was not measured during NEDC testing; * Route 1: rural-motorway for Vehicles A and C (see Table 3) includes a combination of the two test routes Ispra-Milan-Ispra and Milan-urban

In contrast to the on-road NO_X emissions, both on-road CO and THC emissions generally stay below Euro 3-5 emission limits. Figures 15 and 16 indicate that:

(i) On-road CO emissions of both diesel and gasoline vehicles generally stay below Euro 3-5 emission limits.

(ii) The results do not allow identifying a trend towards lower CO emissions from Euro 3 to Euro 5 diesel and gasoline vehicles.

(iii) The Euro 5 gasoline vehicle L shows exceptionally high emissions during extreme uphill-downhill as well as high-speed driving. The high CO emissions are associated with elevated THC emissions (see below) and high catalyst temperatures of up to 400 °C. The insufficient oxidation of carbon monoxide during uphill and high-speed driving points to insufficient catalytic conversion and requires further analyses.

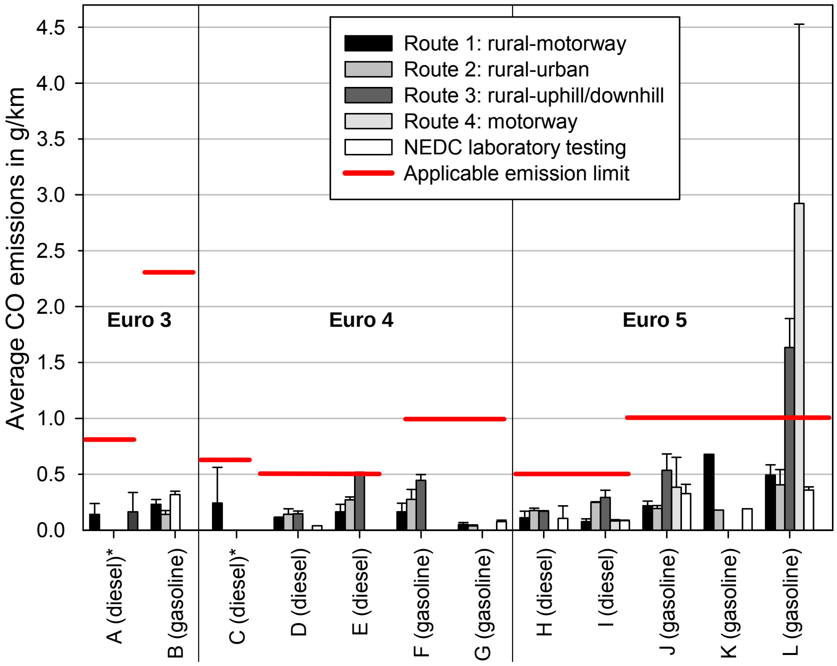


Figure 15: Average CO emissions on the PEMS test routes and during NEDC testing in the laboratory; uncertainty intervals indicate the maximum average emissions for each test route and vehicle; * Route 1: rural-motorway for Vehicles A and C (see Table 3) includes a combination of the two test routes Ispra-Milan-Ispra and Milan-urban

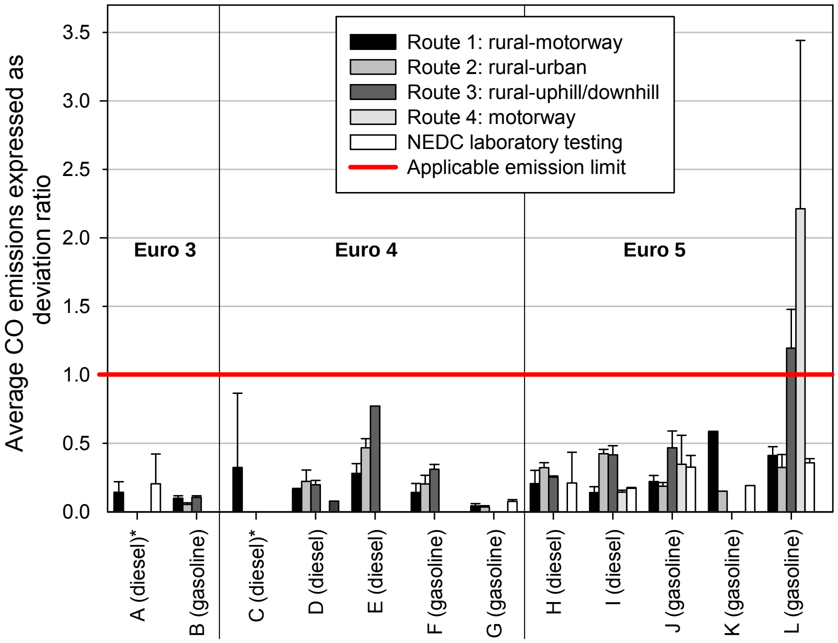


Figure 16: Average CO emissions on the PEMS test routes and during NEDC testing in the laboratory expressed as deviation ratio; uncertainty intervals indicate the maximum emissions for each test route and vehicle; * Route 1: rural-motorway for Vehicles A and C (see Table 3) includes a combination of the two test routes Ispra-Milan-Ispra and Milan-urban

The THC emissions of all diesel and gasoline vehicles remain below Euro 3-5 emission limits during the PEMS test campaign. The results can be summarized as follows (Figures 17 and 18):

(i) THC emissions of diesel and gasoline vehicles remain far below Euro 3-5 emission limits.

(ii) THC emissions generally increase from Euro 3 to Euro 5 gasoline vehicles both in absolute terms and as percentage of Euro 3-5 emission limits.

(iii) THC emissions of diesel and gasoline vehicles are generally higher during NEDC testing than they are on the road.

(iv) The Euro 5 gasoline Vehicle L shows higher THC emissions than all other test vehicles; the elevated emissions are associated with catalyst temperatures of up to 400 °C, suggesting low catalytic conversion rates.

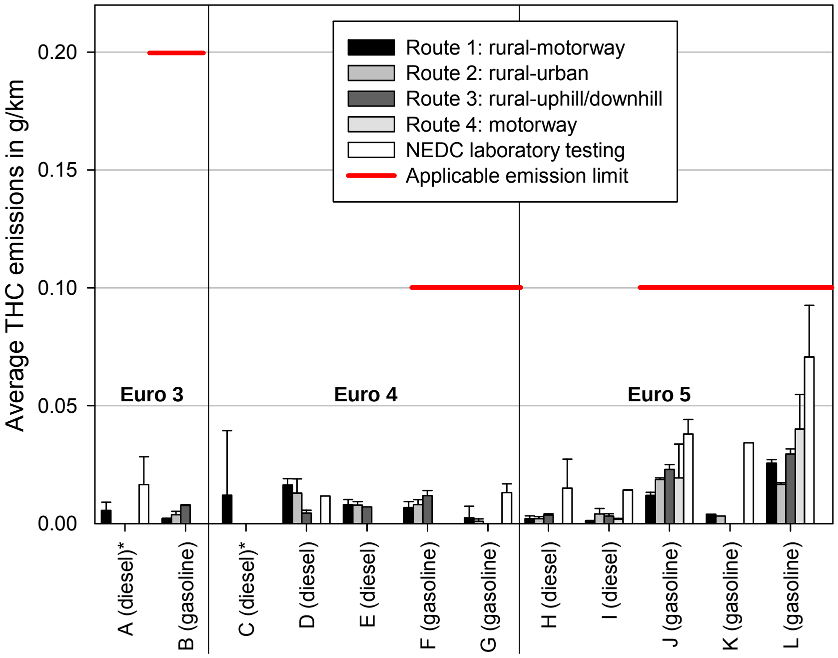


Figure 17: Average THC emissions on the PEMS test routes and during NEDC testing in the laboratory; uncertainty intervals indicate the maximum average emissions for each test route and vehicle; * Route 1: rural-motorway for Vehicles A and C (see Table 3) includes a combination of the two test routes Ispra-Milan-Ispra and Milan-urban

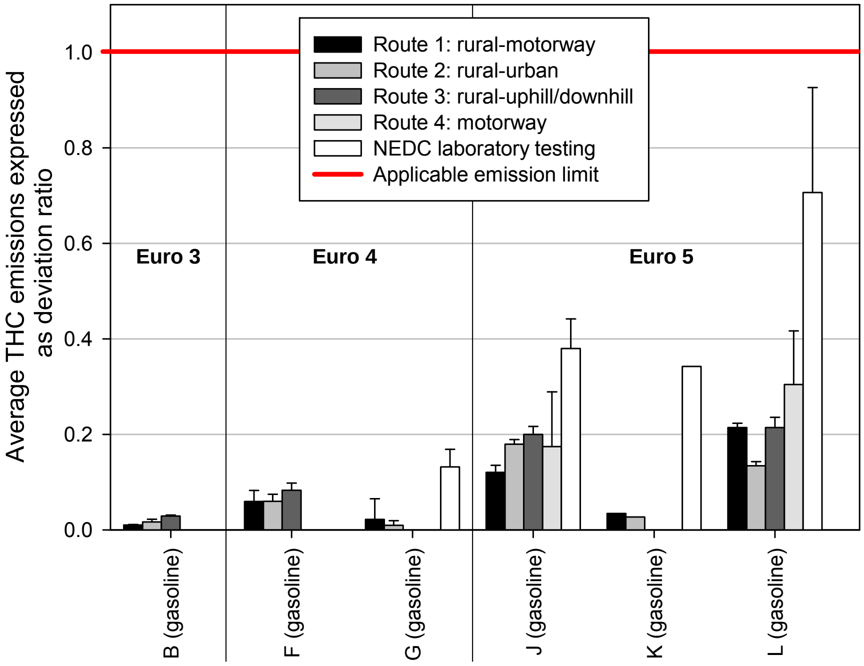


Figure 18: Average THC emissions on the PEMS test routes and during NEDC testing in the laboratory expressed as deviation ratio; uncertainty intervals indicate the maximum average emissions for each test route and vehicle

The PEMS measurements indicated so far that on-road NO_X emissions of diesel vehicles substantially exceed substantially Euro 3-5 emission limits, whereas on-road CO and THC emissions generally remain below the limits. Next to regulated pollutants, on-road CO_2 emissions are of particular interest to policy makers. To reduce greenhouse gas emissions from transport, the European commission sets a target of 130 g CO_2/km for new passenger cars of a reference mass of 1372 kg (EC, 2009a). For reasons of simplicity, we uniformly use here 130 g CO_2/km as benchmark for all test vehicles, thereby disregarding the specific mass of vehicles. The PEMS measurements indicate that (Figures 19-21):

(i) The average on-road CO_2 emissions of all vehicles tested on the four PEMS test routes amount to 176 ± 42 g/km. Diesel vehicles emit on average 189 ± 51 g/km, whereas gasoline vehicles emit 162 ± 29 g/km CO_2. Thus, on-road emissions substantially exceed the European Commissions fleet-average emissions target of 130 g/km (EC, 2009a).

(ii) The on-road CO_2 emissions of test vehicles exceed the emissions as specified during NEDC type approval by on average 21 ± 9%. Diesel vehicles show a deviation of 24 ± 8% and gasoline vehicles of 18 ± 10%. Still, these deviations might increase if vehicles are driven at extremely high speeds, e.g., as it frequently occurs on the German Autobahn.

(iii) The average CO_2 emissions during NEDC laboratory tests exceed the emission values as specified during NEDC type approval by 15 ± 10%. This deviation might be explained by differences regarding vehicle preparation (e.g., brand, dimension, air pressure of tyres, level of battery charge) as well as specific settings of the chassis dynamometer.

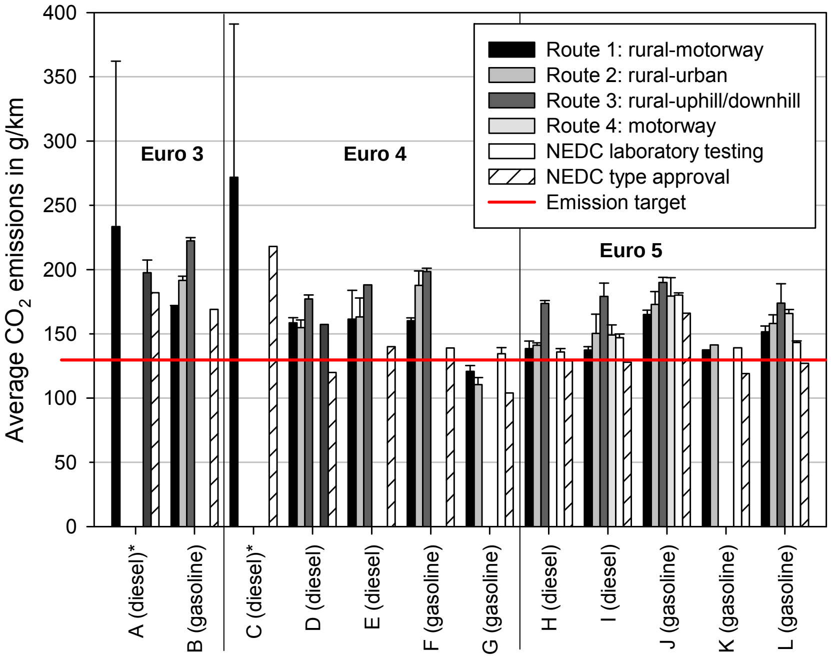


Figure 19: Average CO_2 emissions on the PEMS test routes and during NEDC testing in the laboratory; uncertainty intervals indicate the maximum average emissions for each test route and vehicle; * Route 1: rural-motorway for Vehicles A and C (see Table 3) includes a combination of the two test routes Ispra-Milan-Ispra and Milan-urban; Vehicles A and C belong to vehicle Category N1 and are not subject to the fleet-average emissions target as specified by EC (2009a)

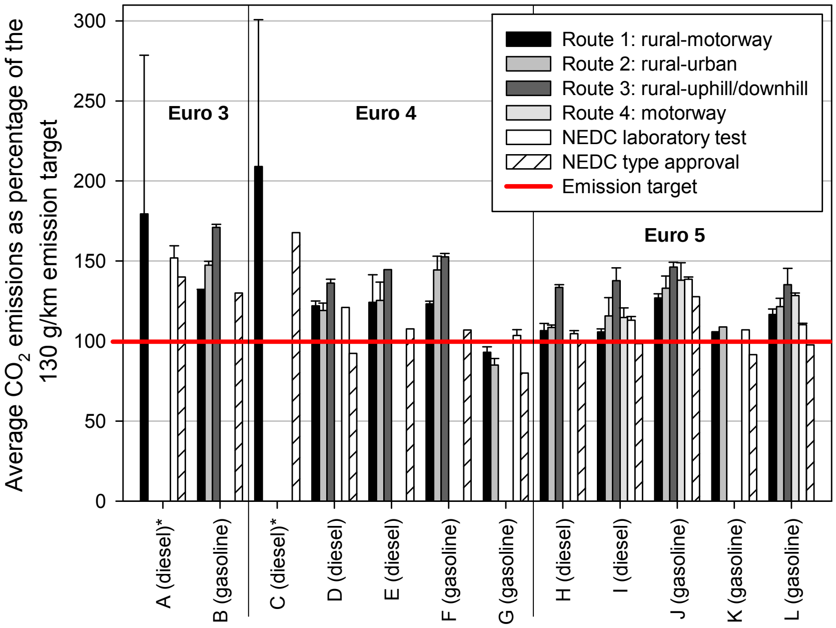


Figure 20: Deviation of average CO_2 emissions on the PEMS test routes and during NEDC testing in the laboratory expressed percentage of the established emission target of 130 g CO_2/km; uncertainty intervals indicate the maximum average emissions for each test route and vehicle; * Route 1: rural-motorway for Vehicles A and C (see Table 3) includes a combination of the two test routes Ispra-Milan-Ispra and Milan-urban; Vehicles A and C belong to vehicle Category N1 and are not subject to the fleet-average emissions target as specified by EC (2009a)

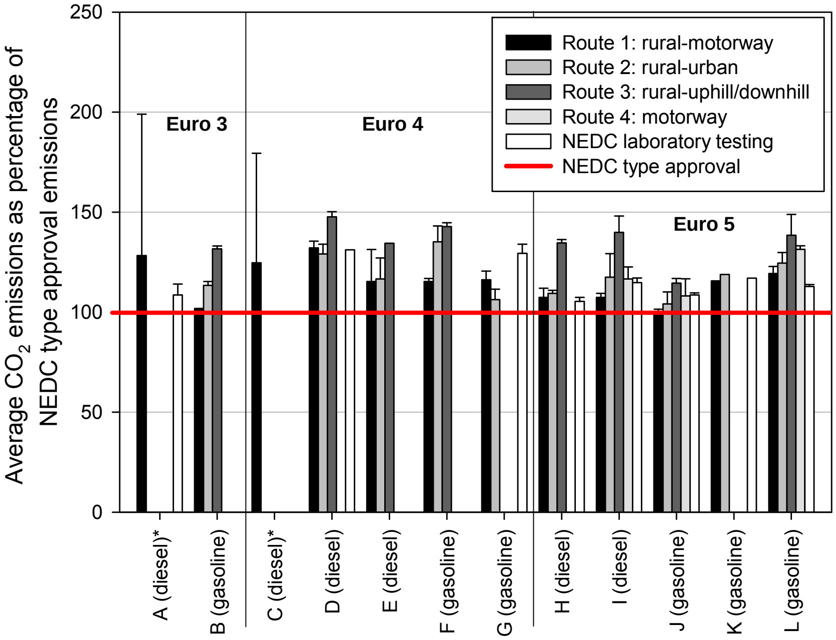


Figure 21: Deviation of average CO_2 emissions on the PEMS test routes and during NEDC testing in the laboratory expressed percentage of the NEDC type approval emissions; uncertainty intervals indicate the maximum average emissions for each test route and vehicle; * Route 1: rural-motorway for Vehicles A and C (see Table 3) includes a combination of the two test routes Ispra-Milan-Ispra and Milan-urban

The report presented so far on-road emissions as averages over entire test routes. The next section analyzes in greater detail the on-road NO_X emissions of Euro 5 vehicles by making use of the averaging window calculations.

4.2 On-road NO_X emissions of Euro 5 light-duty vehicles

4.2.1 On-road NO_X emissions of Euro 5 vehicles versus Euro 5 emission limits

The results of the previous section indicate that on-road NO_X emissions of Euro 5 diesel vehicles may substantially exceed the Euro 5 emission limit. This section analyzes now in greater detail the NO_X emissions of Euro 5 vehicles with the averaging window method (see Section 3.4.2 for methodological details). The analysis shows that for almost any driving conditions the two tested Euro 5 diesel vehicles emit more NO_X than specified by the Euro 5 limit of 0.18 g/km (Figures 22-25). The key findings are:

(i) The average NO_X emissions of all averaging windows exceed the Euro 5 emission limit in the case of Vehicle H; the average NO_X emissions of at least 80% of the averaging windows exceed the Euro 5 emission limit in the case of Vehicle I, depending on the route driven.

(ii) Uphill/downhill driving on Route 3 is associated with particularly high NO_X emissions; the average NO_X emissions of all averaging windows for Vehicles H and I exceed the Euro 5 emission limit on this test route; roughly 20% of the averaging window emissions exceed the Euro 5 limit by more than 8 times. This finding points to fuel consumption, i.e., engine load as critical parameter determining the NO_X emissions of diesel vehicles.

(iii) The distribution of the averaging window NO_X emissions shows considerable variability, which is higher between different test routes than between individual tests on identical test routes.

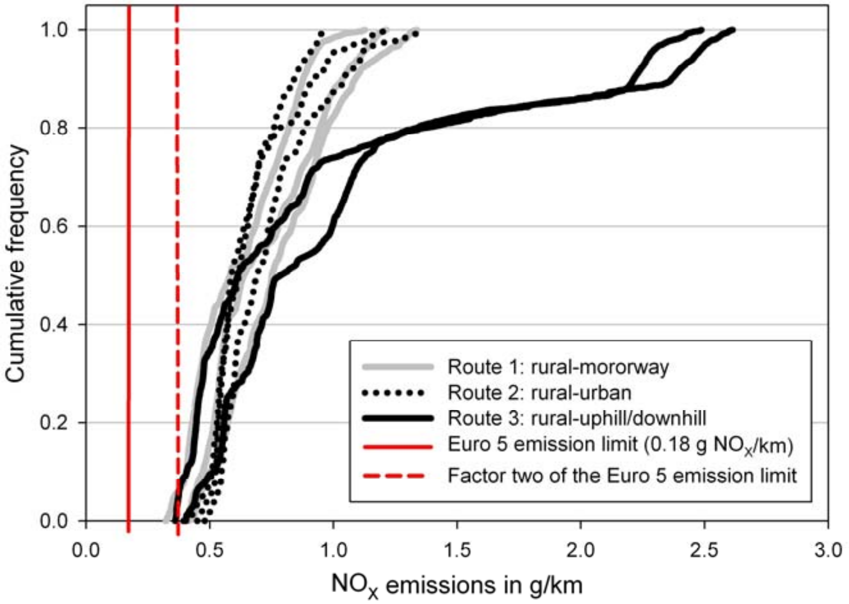


Figure 22: Averaging window NO_X emissions of EURO 5 diesel Vehicle H

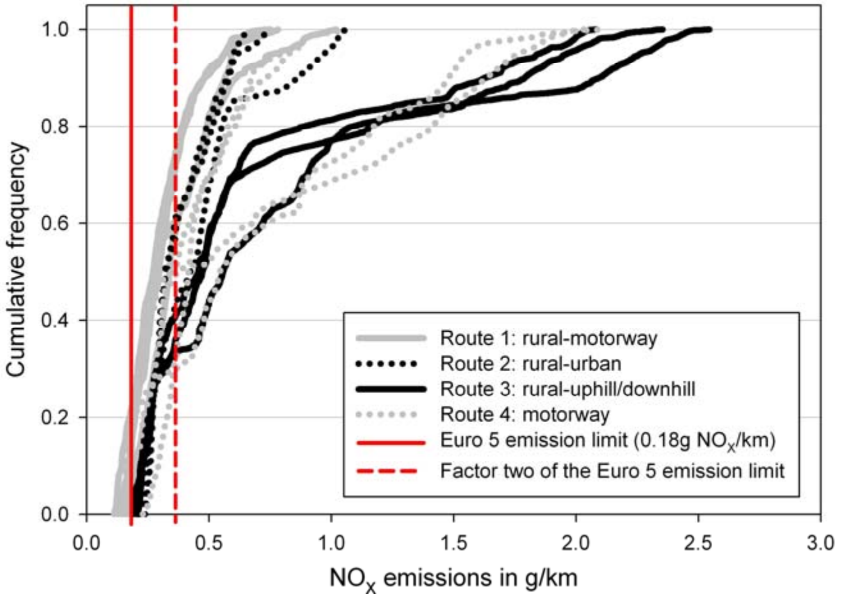


Figure 23: Averaging window NO_X emissions of EURO 5 diesel Vehicle I

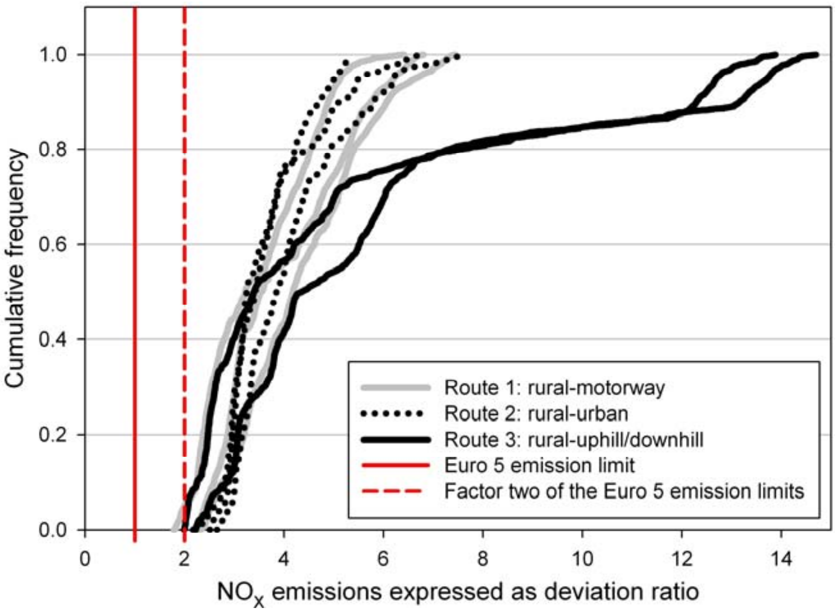


Figure 24: Averaging window NO$_X$ emissions of EURO 5 diesel Vehicle H expressed as deviation ratio

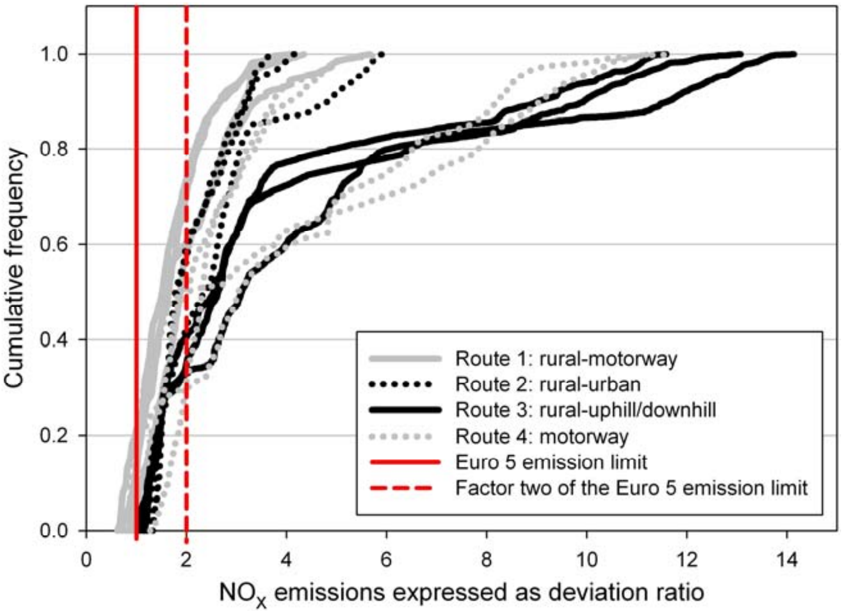


Figure 25: Averaging window NO$_X$ emissions of EURO 5 diesel Vehicle I expressed as deviation ratio

In conclusion, the results indicate that the magnitude of NO$_X$ emissions of Euro 5 diesel vehicles depends on vehicle velocity and operation mode but substantially exceeds under almost all on-road driving conditions the Euro 5 emission limit. This finding presents a sharp contrast to Euro 5 gasoline vehicles, for which NO$_X$ emission remain for most of the averaging windows below the Euro 5 limit of 0.06 g/km (Figure 26). The key findings for Euro 5 gasoline vehicles are:

(i) NO$_X$ emissions remain for the majority of averaging windows below the Euro 5 emission limit.

(ii) Even on the very severe Route 3, at maximum 40% of the averaging windows exceed the Euro 5 emission limit (Vehicle L). However, NO$_X$ emissions of a very few averaging windows might exceed the limit by more than three times under these driving conditions.

(iii) Particularly high NO_X emissions occur at velocities higher than 120 km/h, under extreme uphill/downhill driving, during the cold-start phase, and during idling in urban driving. This finding points to fuel consumption (i.e., engine load) as well as catalyst temperature (which is low during cold start and might decline during long downhill and idling passages) as critical parameters for NO_X emissions. This finding further indicates, which driving pattern should be critically considered during type approval to achieve an effective reduction of on-road NO_X emissions.

(iv) The high NO_X emissions during low-velocity driving on Routes 1 and 2 are likely to be caused by both cold start and long idling periods. In the latter case, the catalyst cools down while the engine produces emissions although the vehicle's velocity is zero.

Caution is, however, required before drawing conclusions about the high emission levels of Euro 5 gasoline vehicles on Routes 1 and 2. Additional evaluation in Section 4.2.3 shall explore to which extent idling actually explains high NO_X emissions at low velocity and whether alternative metrics for data analysis should be employed to correct for the bias introduced by idling operation into the results.

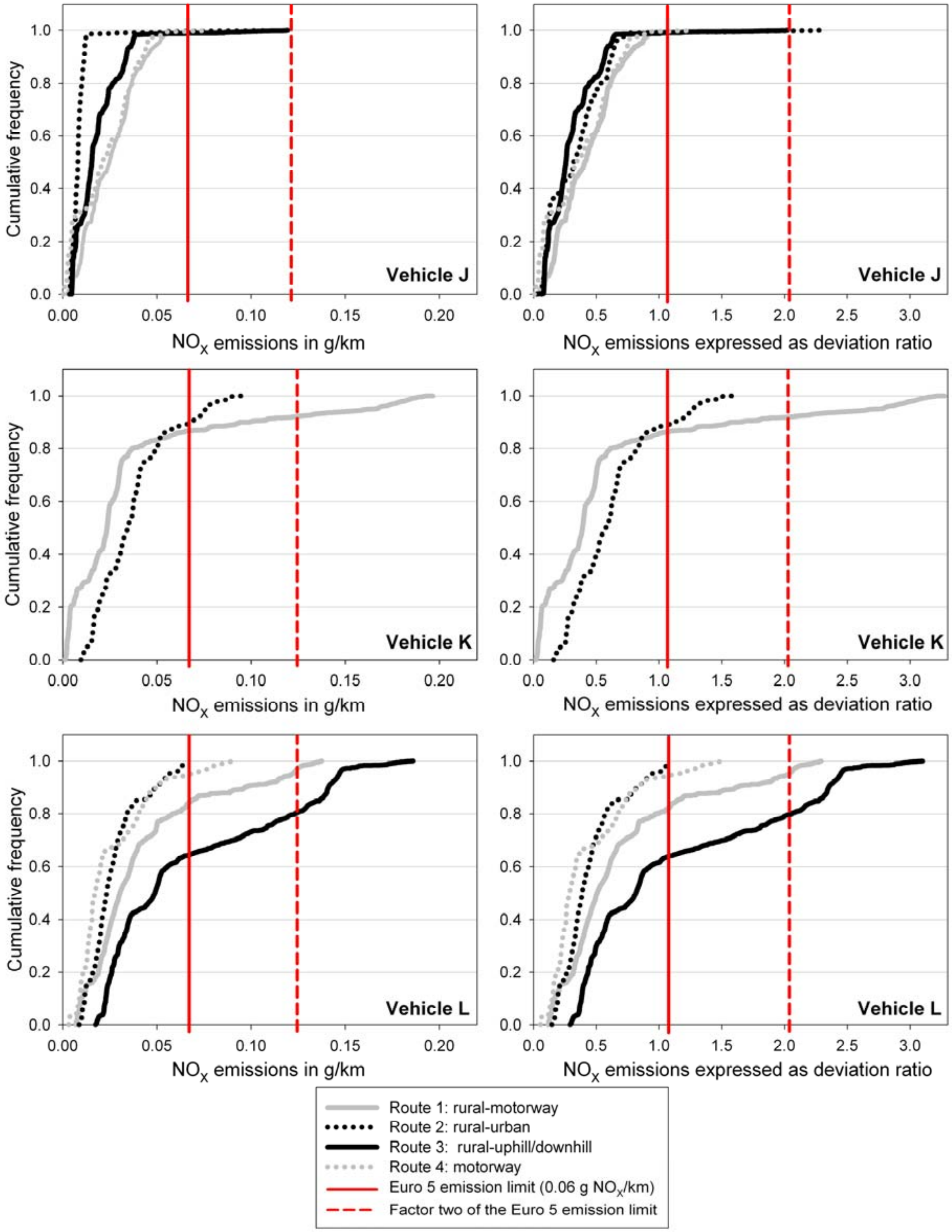


Figure 26: Averaging window NO_X emissions of Euro 5 gasoline vehicles; results given for only one randomly selected PEMS test for each vehicle and test route

4.2.2 Comparison of on-road NO_X emissions of Euro 3-5 vehicles

The previous section focussed solely on Euro 5 vehicles. This section now compares the averaging window NO_X emissions of Euro 3-5 vehicles based on one, randomly selected PEMS test per vehicle and test route (Figures 27 and 28). The findings are consistent with the route-average NO_X emissions identified in Section 4.1 and indicate that:

(i) Averaging window NO_X emissions of diesel vehicles in general substantially exceed the Euro 3-5 emission limit, while varying over a large range of values.
(ii) Averaging window NO_X emissions show a decline from Euro 3 to Euro 5 diesel vehicles, albeit at relatively large variability.
(iii) The highest averaging window NO_X emissions typically occur during demanding uphill/downhill driving on Route 3 and at high speeds on the motorway (Route 4).

By contrast, the findings for gasoline vehicles (Figure 28) indicate that:

(i) The majority of averaging window emissions remains below the Euro 3-5 emission limits although NO_X emissions vary over a large value range.
(ii) A few averaging windows substantially exceed the Euro 3-5 emission limits. These windows often include the cold-start, which is characterized by a low catalyst temperature and thus conversion efficiency.
(iii) The high emissions of Vehicle H on Route 3 present an exception among gasoline vehicles and warrant further and more detailed analyses.

In particular the results for gasoline vehicles indicate substantially elevated emissions during cold start. The next section addresses therefore cold-start emission in greater detail.

Figure 27: Comparison of the averaging window NO_X emissions of Euro 3-5 diesel vehicles on the four PEMS test routes; red solid lines indicate from left to right the Euro 3-5 emission limit; Euro 3 and Euro4 Class II emission limits for Vehicle A and C correspond to 0.65 g NO_X/km and 0.33 g NO_X/km, respectively and are not indicated for reasons of simplicity; red short-dashed lines indicate from left to right the factor one and two of the respective Euro 3-5 emission limit

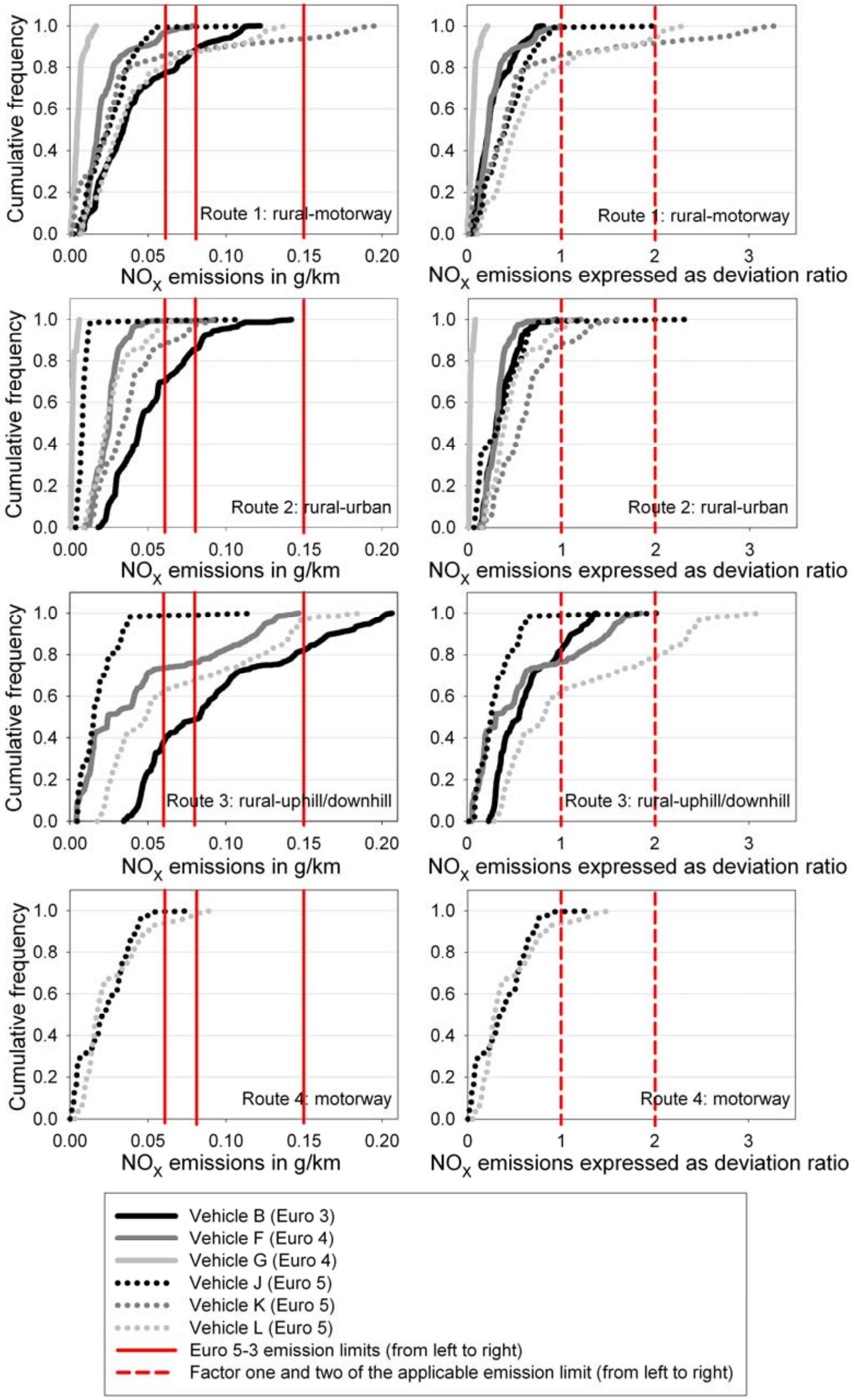


Figure 28: Comparison of the averaging window NO$_X$ emissions of Euro 3-5 gasoline vehicles on the four PEMS test routes

4.3 Cold start emissions

Low catalyst temperatures typically limit the effectiveness of the catalytic conversions during cold start. Cold start emissions are of particular interest because these generally occur in urban areas and might substantially exceed average on-road emissions levels. The analysis of cold-start emissions focuses on the first 300 seconds of each PEMS emissions test. The various test routes were not differentiated because driving conditions are relative similar during this initial time period for all test routes. Cold-start emissions are presented in the following for each light-duty vehicle individually as averages over all four test routes (Figures 29 and 30).

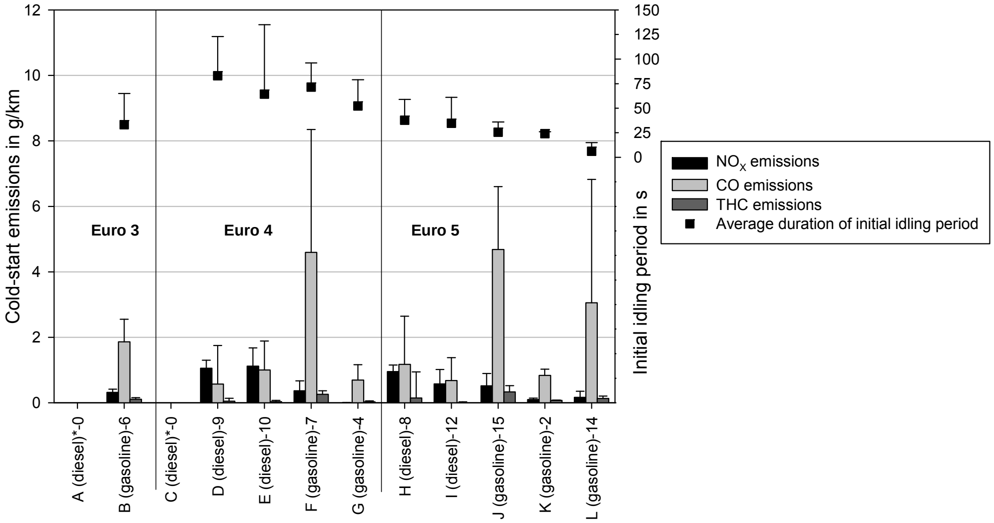


Figure 29: Average cold-start emissions and initial idling periods of light-duty vehicles; numbers below the x-axis indicate the amount of individual PEMS tests included in this analysis; uncertainty intervals indicate the maximum cold-start emissions identified for each respective vehicle; * Vehicles A and C (see Table 3) are excluded because the driving distance during the cold-start period could not be retrieved from the GPS system

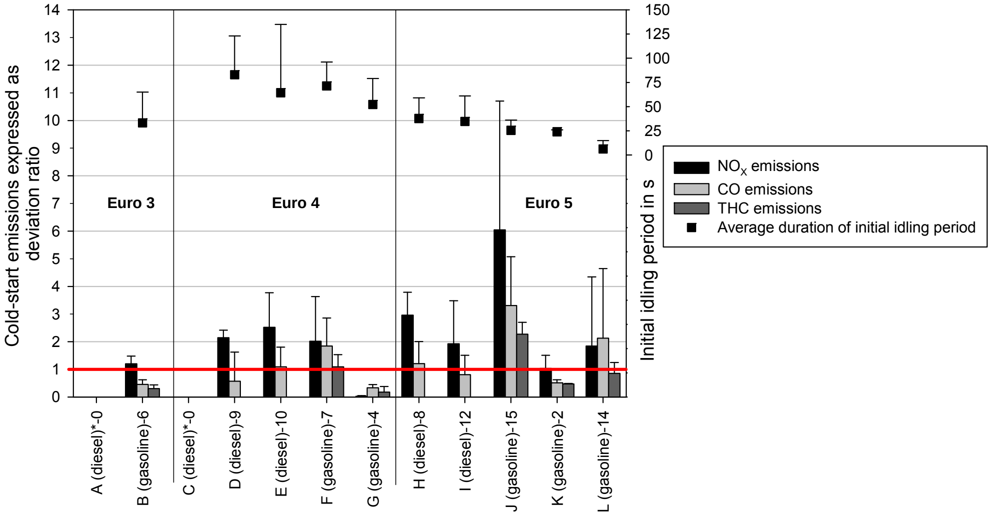


Figure 30: Average cold-start emissions expressed as deviation ratio and initial idling periods of light-duty vehicles; numbers below the x-axis indicate the amount of individual PEMS tests included in this analysis; uncertainty intervals indicate the maximum cold-start emissions identified for each respective vehicle; * Vehicles A and C (see Table 3) are excluded because the driving distance during the cold-start period could not be retrieved from the GPS system

The results presented in Figures 29 and 30 can be summarized as follows:

(i) The data do not indicate a trend towards lower cold-start emissions from Euro 3 to Euro 5 diesel and gasoline vehicles.

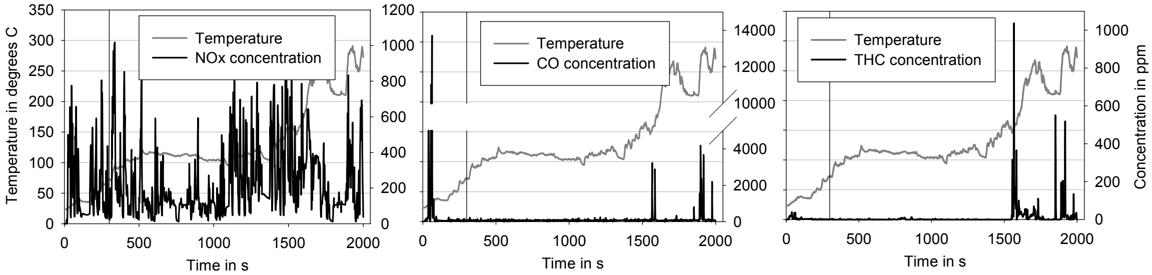
(ii) Cold-start emissions of both diesel and gasoline vehicles generally exceed Euro 3-5 emission limits. Cold-start NO_X emissions are always higher than the Euro 3-5 limits; CO emissions often exceed the emission limits; THC emissions are both below and above the Euro 3-5 limits.

(iii) Cold-start emissions are slightly higher than the average on-road emissions in the case of NO_X but substantially exceed the average on-road emissions in the case of CO and THC.

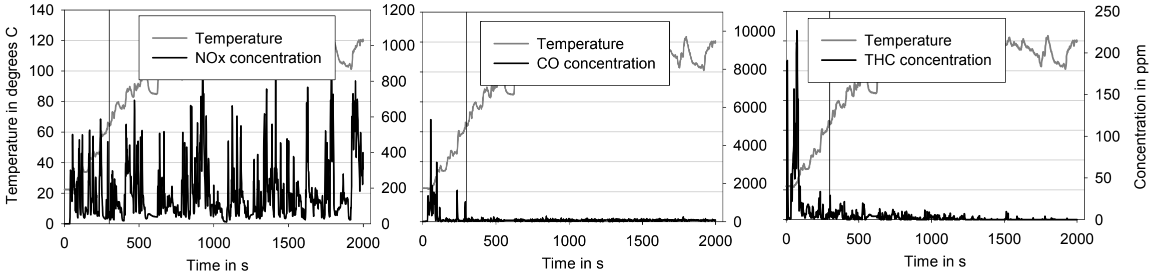
(iv) Cold-start emissions of individual vehicles span over a relative large value range. This suggests that environmental conditions (e.g., lower or higher ambient temperatures) in combination with changing driving pattern (e.g., longer or shorter idling periods) might substantially affect the results. In particular the duration of initial idling periods might have a substantial effect on the distance-specific cold-start emissions. More detailed analysis is warranted to quantify the magnitude of this effect on the results presented in Figures 29 and 30.

More detailed insights into cold-start emission pattern can be obtained by plotting both emissions and tailpipe temperature as function of time (Figures 31 and 32). The examples of diesel Vehicle H and gasoline Vehicle L indicate that pollutant concentrations in the exhaust are often particularly high directly after the start of the engine. At this point, exhaust and catalyst temperatures are particularly low, causing a low efficiency in the oxidation of CO and THC. The NO_X concentrations in the exhaust of diesel Vehicle H show large fluctuations but no obvious temperature dependency in the cold start phase. This finding results from the absence of catalytic NO_X oxidation in the emissions treatment system. By contrast, NO_X concentrations in the exhaust of gasoline Vehicle L decline directly after engine start. This finding points again to the temperature-dependent efficiency of three-way catalysts in gasoline vehicles.

Route 1: Ispra-Milan-Ispra:



Route 2: Ispra-Varese-Ispra:



Route 3: Ispra-Sacro Monte-Ispra:

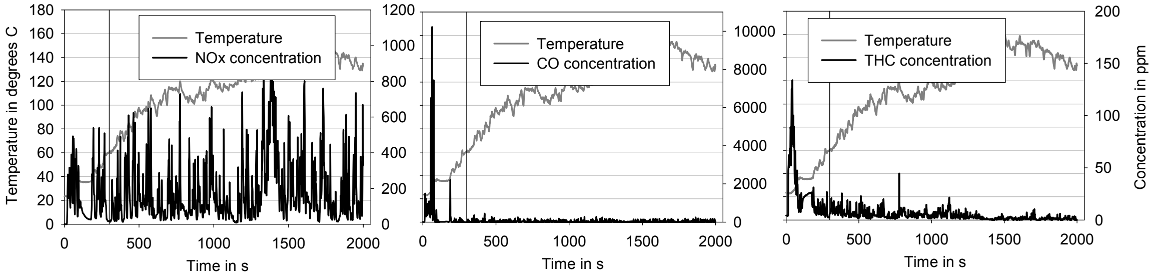
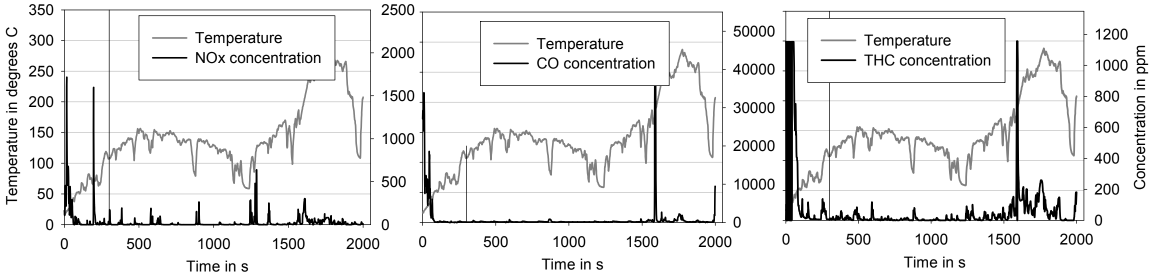
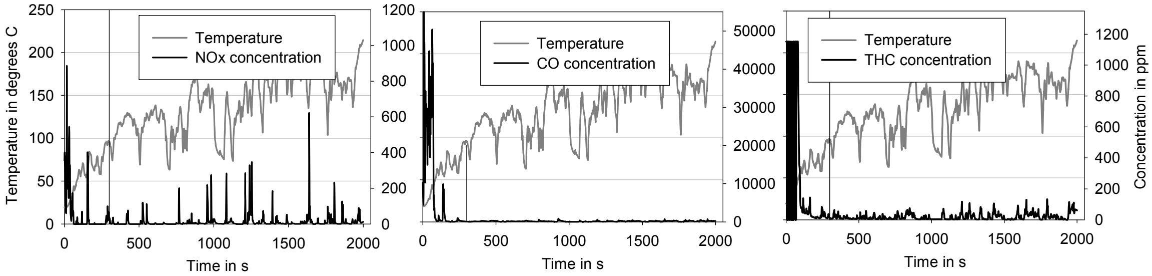


Figure 31: Cold start exhaust pollutant concentrations of Euro 5 diesel Vehicle H

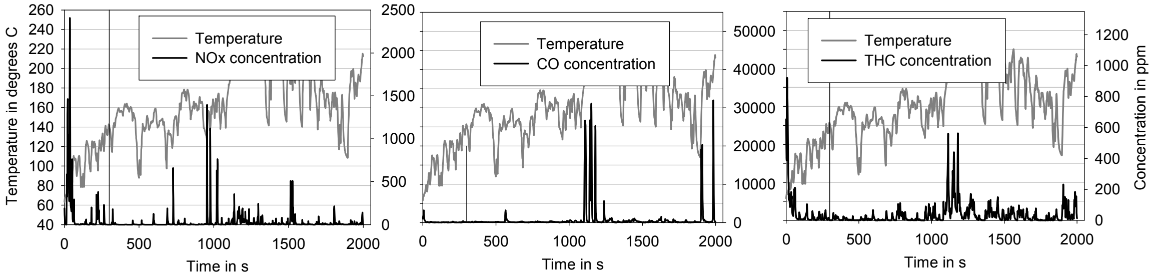
Route 1: Ispra-Milan-Ispra:



Route 2: Ispra-Varese-Ispra:



Route 2: Ispra-Sacro Monte-Ispra:



Route 4: High speed driving:

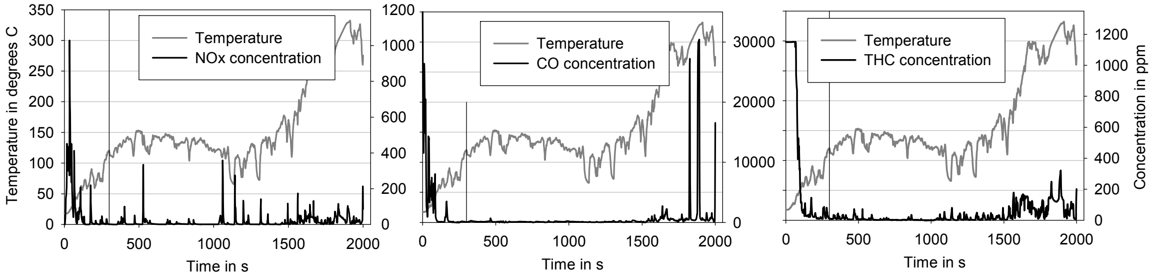


Figure 32: Cold start exhaust pollutant concentrations of Euro 5 gasoline Vehicle L

5 Discussion

5.1 Data analysis and results

The on-road PEMS measurements indicate that in particular on-road NO_X emissions of light-duty diesel vehicles substantially exceed the Euro 3-5 emission limits, whereas on-road CO and THC emissions generally remain below the Euro 3-5 emission limits. These findings can be regarded as reliable and robust. Interpreting the deviation ratios of averaging window emissions, however, deserves special attention because this parameter differs from the so-called conformity factor that is used to characterize emissions of heavy duty vehicles (EC, 2010). First we reiterate the methodology for calculating both deviation ratios and conformity factors. Afterward, a comparison of deviation ratios and conformity factors calculated as a sample case for the averaging window emissions of one selected light-duty vehicle is presented.

Section 3.4.2 describes in detail the methodology for calculating deviation ratios. Conformity factors are calculated based on a similar method, with the exception that now engine work is used as reference quantity instead of travel distance as it is the case for deviation ratios (see Section 3.4.2). This approach is chosen to assure consistency with both the method used to define the duration of averaging windows and the definition of emission limits for heavy-duty vehicles (Bonnel and Kubelt, 2010; EC, 2009b, 2010).

To analyze the differences between the two parameters, also conformity factors for one light duty vehicle were calculated as a sample case. For this calculation, we approximate engine work by the CO_2 mass emitted. Per definition, the cumulative CO_2 mass emitted during one averaging window equals the cumulative CO_2 mass emitted during a standard NEDC test. Therefore, the conformity factor simplifies in this sensitivity analysis to the quotient of measured averaging window emissions and the respective Euro 5 emission limit (see also Equations 3-5 in Section 3.4.2):

$$CF = \frac{CF_I}{CF_C} = \frac{\dfrac{m}{m_{CO_2}(t_2) - m_{CO_2}(t_1)}}{\dfrac{m_L}{m_{CO_2;NEDC}}} = \frac{m}{m_L} \text{ ,if} \qquad (\textit{Equation 7})$$

$$m_{CO_2}(t_2) - m_{CO_2}(t_1) = m_{CO_2;NEDC} \qquad (\textit{Equation 8})$$

where:
CF = conformity factor
CF_I = in-use conformity factor
CF_C = certification conformity factor
m = mass of emissions; indices having the same meaning as in Equations 3-5

Based on this calculation, it is now possible to understand the difference between deviation ratio and conformity factor: In the case of the deviation ration, the distance driven by a vehicle on the road most likely differs from the distance of the NEDC cycle, even if the CO_2 masses on-road and during NEDC testing are identical. For example, if a vehicle is driven on the challenging uphill/downhill Route 3, it might consume more fuel, thus emit more CO_2 than under NEDC condition, and thus travelling a shorter distance until it has emitted a CO_2 mass equivalent to the one emitted during NEDC testing. In such a case, the deviation ratio increases by the fraction of window distance to NEDC distance. Consequently, it is precisely this fraction between window distance and NEDC distance that represents the difference between deviation ratio and conformity factor. Since the measured on-road fuel consumption and the associated CO_2 emissions exceed the CO_2 emissions during NEDC testing by on average 21 ± 9% (see Section 4.1) it can be expected that the deviation ratio generally exceeds the conformity factor. Figure 33 indicates that this is indeed the case in our sample analysis for Vehicle L.

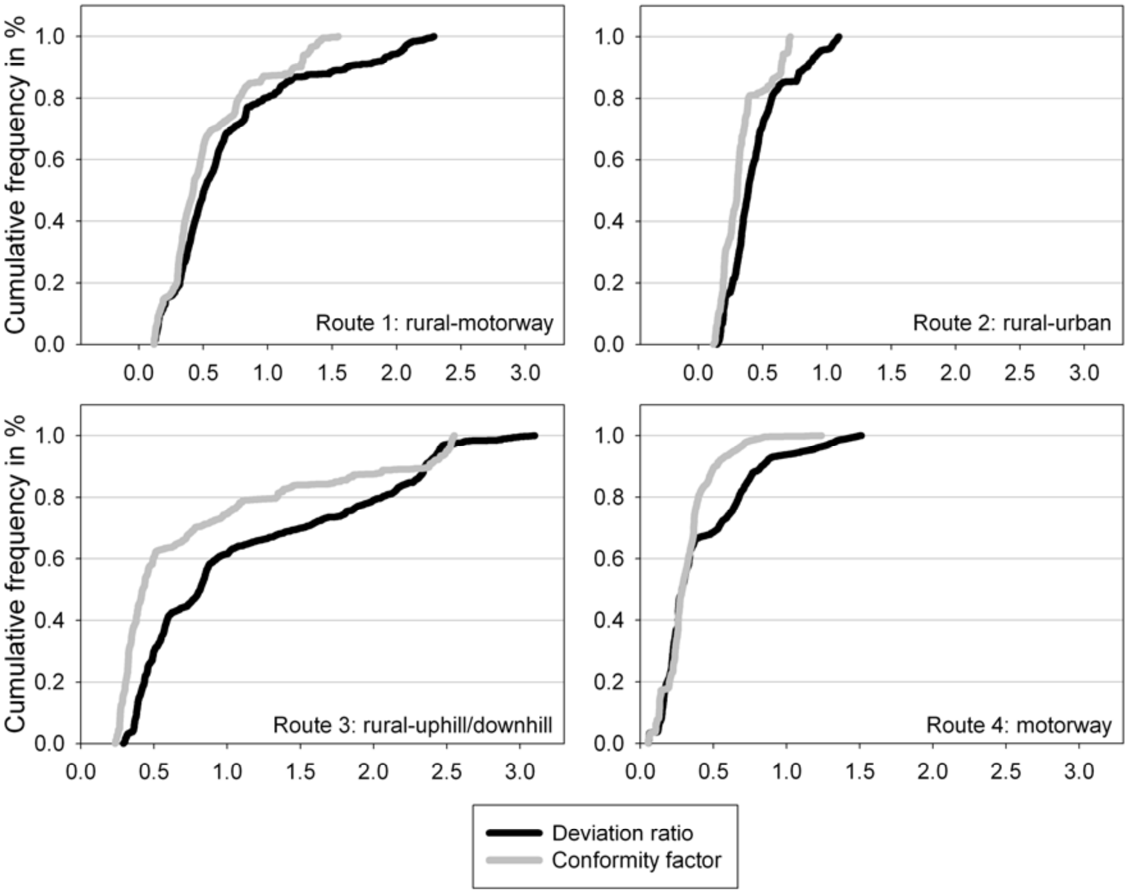


Figure 33: Cumulative frequency distribution of averaging window NO_X emissions of Vehicle L expressed as deviation ratio and conformity factor

By focusing in detail on Route 1, the data furthermore indicate that both deviation ratio and conformity factor of averaging window NO_X emissions show a positively skewed distribution (Figure 34). The peak of the frequency distribution of deviation ratios is located at 0.37, whereas the peak of the distribution of conformity factors is located at 0.28. A similar pattern can also be expected for other vehicles and pollutant emissions. This finding indicates that the majority of emissions are slightly lower than the average, while for a minority averaging windows, emissions are substantially elevated.

The distinct properties of deviation ratio and conformity factor suggest that both parameters should serve slightly different purposes:

(i) The deviation ratio is best used to indicate the ratio of distance-specific emissions to distance-specific emission limits as specified for light-duty vehicles.

(ii) The conformity factor serves best to compare work-specific emissions with work-specific emission limits as specified for heavy-duty vehicles.

The conformity factor is independent of distance; it may therefore provide a robust evaluation of emissions during long idling periods. In the case of idling, the distance travelled during in an averaging window may decrease substantially and theoretically lead to a considerable increase in the deviation ratio. This problem links to the shortcoming of a distance-specific definition of emission limits for light-duty vehicles that does not permit to link emissions to actual engine parameters.

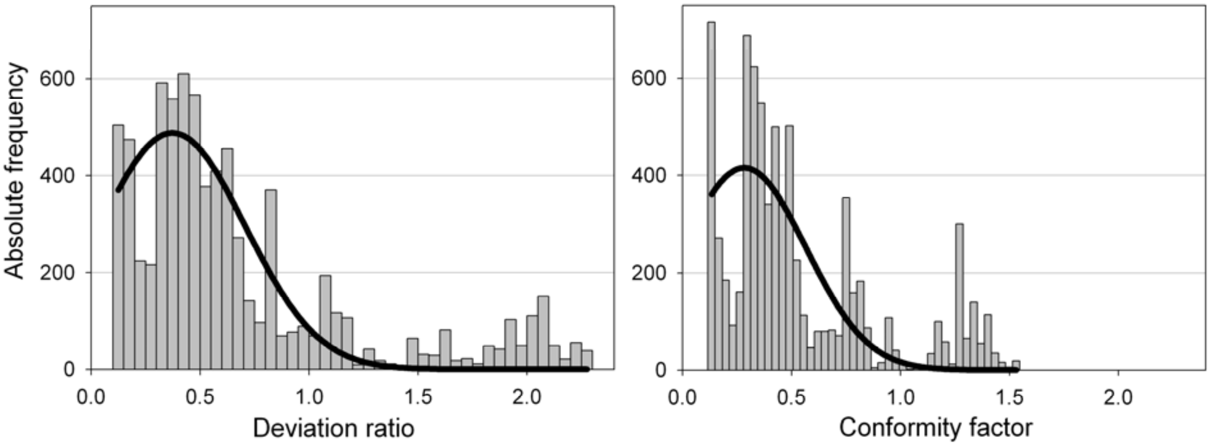


Figure 34: Cumulative frequency distribution of averaging window NO_X emissions of Vehicle L on test Route 1 expressed as deviation ration and conformity factor

On-road emissions testing with PEMS allows covering a large variety of driving conditions and is typically characterized by a high degree of randomness and limited repeatability. The variability in road, weather, and traffic conditions as well as the drivers' behaviour attribute to every on-road PEMS test quasi unique characteristics. Nevertheless, these characteristics open the possibility for limiting on-road PEMS tests to a very narrow range of normal driving conditions, e.g., with the aim of achieving extremely low emission values. Given this limitation, it is imperative:

(i) to continue using a standardized laboratory emissions test procedure that yields comparable and reproducible emission results

(ii) to supplement this procedure by test procedures that capture a wider range of potential on-road emissions

(iii) to define general criteria for conducting on-road PEMS tests

5.2 Potentials of PEMS-based emission test procedures

The present test campaign revealed the strengths and weaknesses of PEMS. In view of developing supplementary emission test procedures for light-duty vehicles, these can be summarized as follows:

Strengths:

(i) PEMS measures real emissions from actual on-road driving.

(ii) PEMS can assure the proper design and operation of emission control technologies as well as the vehicle's energy consumption under a wide variety of normal operating conditions.

(iii) PEMS is suitable to test emissions from novel engine/after-treatment/powertrain technologies (e.g., parallel/serial (plug-in) hybrids or electric vehicles) as well as from alternative fuels.

(iv) PEMS provides measurements that can serve as basis for not-to-exceed emission limits, i.e., emission levels that should not be exceeded, regardless of driving and ambient conditions.

Weaknesses:

(i) PEMS generally allow only to a very limited extent to reproduce and compare individual test results due to the variability of on-road ambient and driving conditions.

(ii) PEMS allow only to a limited extent to reproduce cold start emissions.

(iii) The power consumption of PEMS is typically supplied by auxiliary batteries in order not to interfere with the vehicle operation. However, the weight of batteries and analytical equipment of approximately 80 kg may introduce a bias in emission measurements, especially if conducted for small vehicles equipped with small engines. Potentials for weight reductions of the equipment exist as technological improvements of the test equipment are very likely (both in terms modularity and size).

Several practical considerations might support or limit the application of PEMS:

(i) PEMS allows for relatively long test campaigns of 2 hours duration.

(ii) PEMS test procedures and equipment has been developed for testing the in-service conformity of heavy-duty vehicles and non-road machinery and has been proven to be reliable also for light-duty vehicles.

(iii) The modular composition of PEMS allows for limiting the emissions screening to an absolute minimum. For instance, the THC measurements with an FID analyser (which has high power consumption and requires a hydrogen/helium mixture) could be abolished because the correct functioning of oxidation and three-way catalysts can also be verified by analysing CO emissions only. Such an approach would reduce the weigh of the PEMS equipment substantially.

(iv) PEMS testing requires no detailed prescription of driving and ambient conditions; a prescription of key-features of test routes (e.g., percentage of driving in city, motorway, test duration, road slope, drivers' behaviour) is, nevertheless, recommended to assure that PEMS testing covers as far as possible the large spectrum of driving conditions as it occurs during normal conditions of vehicle use.

6 Conclusions

This report analyzes the on-road emissions of twelve light-duty diesel and gasoline vehicles by using Portable Emission Measurement Systems (PEMS). The analyses were conducted for Euro 3-5 light-duty vehicles in the period between 2007 and 2010 on four test routes comprising rural, urban, uphill/downhill, and motorway driving.

The average NO_X emissions of all tested diesel vehicles over the entire test routes amount to 0.93 ± 0.39 g/km; the average NO_X emissions of the tested Euro 5 diesel vehicles reach 0.62 ± 0.19 g/km. These results indicate that NO_X emissions of light-duty diesel vehicles substantially exceed the Euro 3-5 emission limits: the route-average NO_X emissions of the tested diesel cars reach 325 ± 90% of the respective emissions limit; the NO_X averages over individual averaging windows may, however, reach up to a factor of 14 of the respective emissions limit. The increasing stringency of European emission limits has, thus, not resulted in an equivalent reduction of on-road NO_X emissions of light-duty diesel vehicles. By comparison, on-road NO_X emissions of gasoline vehicles as well as CO and THC emissions of diesel and gasoline vehicles generally stay within Euro 3-5 emission limits. The share of NO_2 in the total NO_X emissions reaches 60% for diesel vehicles but only 0-30% for gasoline vehicles. The tested light-duty diesel and gasoline vehicles emit on average 189 ± 51 g CO_2/km (grams of carbon dioxide per kilometre) and 162 ± 29 g CO_2/km, respectively during on-road testing, thereby exceeding the CO_2 levels as specified during NEDC testing of the respective vehicles by on average 21 ± 9%. The magnitude of all pollutant emissions varies depending on vehicle, operation mode, route characteristics, and ambient conditions. Cold-start emissions of both diesel and gasoline vehicles span over a large value range; NO_X emissions exceed Euro 3-5 emission limits by a factor 2-14, CO emissions often exceed the Euro 3-5 limits, and THC emissions are both below and above the limits.

In conclusion, the PEMS results indicate that on-road NO_X emissions of light-duty diesel vehicles differ substantially between laboratory NEDC testing and actual on-road driving. While the standardized laboratory NEDC emissions testing yields comparable and reproducible results, the procedure may fail to capture the potential range of on-road emissions. To solve this shortcoming, Regulation 715/2007 (EC, 2007a) envisages supplementing the standard laboratory emissions testing with suitable complementary test procedures. Such complementary procedures may then also address particularly polluting driving modes, which cannot be simulated in the laboratory such as (i) extreme high speed driving as it frequently occurs on the German Autobahn and (ii) vehicle operations associated with relatively low or high temperatures of the aftertreatment systems. Without covering such a wide range of normal operating conditions, a reduction of on-road emissions, and specifically NO_X emissions, may remain punctual.

The PEMS equipment is able to provide reliable and accurate on-road emission measurements for light-duty vehicles, even for vehicles that will be certified according to future emissions standards. This makes PEMS a suitable tool for identifying and updating emission factors of air pollution models. Furthermore, PEMS may be used as supplemental emission test procedure next to standardized laboratory emission tests. The strengths of PEMS include the ability to detect the proper operation of emission control technologies under a wide variety of normal operating conditions, in particular during high-speed driving at speeds above130 km/h as it frequently occurs on the German Autobahn. PEMS also allows testing emissions from novel fuel/engine/after-treatment/powertrain technologies (e.g., parallel/serial (plug-in) hybrid vehicles. Such analyses have not been conducted yet but are envisaged for the future. A major limitation of PEMS refers to its relatively high weight (PEMS unit, EFM, mounting devices, power supply), which may reach 80 kg (i.e., equal to 1 person). As technological improvements of the test equipment are very likely (in terms modularity and size) the weight of the equipment could be reduced substantially in the future. In conclusion, the present test campaign has resulted in the successful application of PEMS for light-duty vehicles. The results of this test campaign indicate that on-road emissions might exceed substantially emission levels as identified during type approval in the laboratory.

The applied averaging window method, which has been implemented to check emissions of heavy-duty engines (EC, 2010), offers a simple and straightforward way to average and analyze emissions data of light-duty vehicles. Based on this method, appropriate indicators could be developed to evaluate whether an averaging window (or any other data sub-set) can be classified as extreme (as opposed to normal) driving conditions. Such analysis could address specific driving situations, for instance cold start, steep road grades, or aggressive high-speed driving.

Future research should address not-to-exceed regulatory concepts and alternative metrics for defining emission limits: the current approach that expresses emission limits as distance-specific quantities is problematic because it lacks a reference to actual engine parameters and only insufficiently accounts for the large variability of on-road driving conditions that may include long idling periods in congested traffic.

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