Environmental Science & Technology

ARTICLE

pubs.acs.org/est

On-Road Emissions of Light-Duty Vehicles in Europe

Martin Weiss,*,† Pierre Bonnel,† Rudolf Hummel,† Alessio Provenza,† and Urbano Manfredi†

†European Commission — DG Joint Research Centre, Institute for Energy and Transport, Sustainable Transport Unit, Via Enrico Fermi 2749 - TP 230, 21010 Ispra, Italy

S Supporting Information

ABSTRACT: For obtaining type approval in the European Union, light-duty vehicles have to comply with emission limits during standardized laboratory emissions testing. Although emission limits have become more stringent in past decades, light-duty vehicles remain an important source of nitrogen oxides and carbon monoxide emissions in Europe. Furthermore, persisting air quality problems in many urban areas suggest that laboratory emissions testing may not accurately capture the on-road emissions of light-duty vehicles. To address this issue, we conduct the first comprehensive on-road emissions test of light-duty vehicles with state-of-the-art Portable Emission Measurement Systems. We find that nitrogen oxides emissions of gasoline vehicles as well as carbon monoxide and total hydrocarbon emissions of both diesel and gasoline vehicles generally remain below the respective emission limits. By contrast, nitrogen oxides emissions of diesel vehicles (0.93 ± 0.39 grams per kilometer [g/km]), including modern Euro 5 diesel vehicles (0.62 ± 0.19 g/km), exceed emission limits by 320 ± 90%. On-road carbon dioxide emissions surpass laboratory emission levels by 21 ± 9%, suggesting that the current laboratory emissions testing fails to accurately capture the on-road emissions of light-duty vehicles. Our findings provide the empirical foundation for the European Commission to establish a complementary emissions test procedure for light-duty vehicles. This procedure could be implemented together with more stringent Euro 6 emission limits in 2014. The envisaged measures should improve urban air quality and provide incentive for innovation in the automotive industry.

INTRODUCTION

For obtaining type approval in the European Union, light-duty vehicles have to comply with emission limits during standardized laboratory emissions testing.[1−4] Although Euro 1−5 tier emission limits have become more stringent over the past two decades, in 2008 light-duty vehicles still contributed around 8% and 27% to the overall NO_X (nitrogen oxides) and CO (carbon monoxide) emissions of the European Union (EU).[5,6] These shares can be substantially higher in urban areas where 16% of the population is currently exposed to NO_2 (nitrogen dioxide) concentrations that exceed established air quality standards.[7]

The European legislator has responded to this situation by introducing more stringent Euro 6 emission limits that will be enforced on light-duty vehicles from September 2014 onward.[2,3] Major concerns, however, persist because actual on-road emissions of light-duty vehicles may substantially exceed the emission levels as determined during type approval in the laboratory. Several studies have indicated that, in particular, NO_X emissions may be substantially elevated when Euro 2−4 light-duty diesel vehicles are driven on the road.[8−10] Nevertheless, a comprehensive analysis of on-road emissions that includes modern Euro 5 light-duty diesel and gasoline vehicles is still unavailable. Here, we address this knowledge gap by using state-of-the-art Portable Emission Measurement Systems (PEMS) to analyze the on-road emissions of 12 Euro 3−5 light-duty diesel and gasoline vehicles.

We aim at identifying whether the on-road emissions of light-duty vehicles substantially exceed emission limits enforced during type approval. Addressing this issue allows advancing two main areas of emissions control:

(i) Emissions modeling: The results can be used to verify and potentially improve the reliability of emission factors used for projecting the impacts of current and future emission limits on air quality.

(ii) Emissions legislation: The results can demonstrate the necessity of developing a complementary emissions test procedure for the type approval of Euro 6 vehicles from September 2014 onward.[2]

BACKGROUND AND METHODOLOGY

Consistent with European legislation, we define light-duty vehicles as four-wheel road vehicles, for which emissions testing during type approval is conducted based on the entire vehicle. Light-duty vehicles typically include (i) passenger vehicles of categories M_1 and M_2 with no more than eight seats and a

Received: March 15, 2011
Revised: August 1, 2011
Accepted: August 4, 2011
Published: August 04, 2011

maximum mass of 5 tons as well as (ii) vehicles used for the carriage of goods of the categories N_1 and N_2, with a maximum mass of 12 tons.[11] On these vehicles, the European Commission currently enforces Euro 5 tier emission limits for THC (total hydrocarbons), NMHC (nonmethane hydrocarbons), NO_X (nitrogen oxides), THC+NO_X (sum of total hydrocarbons and nitrogen oxides), CO (carbon monoxide), and PM (particulate matter)[2,3] (see Table 1 in the Supporting Information). The manufacturers have to ensure that vehicles comply under normal conditions of use with the emission limits up to a mileage of 100,000 km or a duration of 5 years.[2] In addition, light-duty gasoline vehicles must comply with emission limits of 15 g/km for CO and 1.8 g/km for THC during a low temperature test at −7 °Centigrade.[12] Carbon dioxide (CO_2) emissions are currently unregulated within the EU at the level of individual vehicles. The European Commission, however, defines from 2012 onward a target of 130 g/km for the fleet-average CO_2 emissions of new passenger cars.[13]

The compliance of light-duty vehicles with emission limits is verified by standardized laboratory emissions testing on chassis dynamometers. The New European Driving Cycle (NEDC) is used as test cycle within the EU, ensuring that emission measurements can be compared and reproduced in the type approval of light-duty vehicles[4] (see Figure 1 in the Supporting Information). Emissions are expressed as averages over the entire NEDC in grams per kilometer [g/km]. The NEDC inherits, however, the limitation that it captures only a limited range of on-road driving conditions due to its smooth acceleration profile[14] and its narrow range of engine operation points.[15] Moreover, emissions testing solely based on a single driving cycle faces the risk that engine control technology detects the cycle and optimizes the emissions performance for a set of specific operating conditions. Therefore, it is possible that vehicles comply with emission limits during laboratory testing while exhibiting substantially higher emissions on the road. The European emissions legislation accounts for this potential problem by mandating the European Commission to investigate the actual on-road emissions of light-duty vehicles and to adapt, if necessary, the current test procedures.[2] This mandate forms the basis for our research.

Test Vehicles and Test Routes. The fleet of test vehicles consists of 12 light-duty vehicles of category M_1 and N_1,[11] comprising 5 Euro 3−5 gasoline vehicles (Vehicles B, F, J, K, L); 1 Euro 4 gasoline-hybrid vehicle (Vehicle G); and 6 Euro 3−5 diesel vehicles (Vehicles A, C, D, E, H, I) (see Table 2 in the Supporting Information). Standard commercial fuels are used for all emission tests.

All PEMS on-road tests are conducted at the Vehicle Emissions Laboratory (VELA) of the Institute for Energy and Transport at the Joint Research Centre (JRC) of the European Commission in Ispra, Italy. We use four standard test routes, which reflect, as far as possible, the diversity of on-road driving in Europe: Route 1 covers rural, urban, and motorway driving, Route 2 covers rural and urban driving, Route 3 covers rural and severe uphill-downhill driving, and Route 4 covers, in large shares, motorway driving (see Figures 2 and 3 in the Supporting Information). Vehicles I, J, and L are tested on all four test routes; Vehicles B, D, E, F, and H are tested on Routes 1−3; Vehicles G and K are tested only on Routes 1 and 2. Vehicles A and C are tested in an early project phase on local routes, representing a mix of rural, urban, and motorway driving. These routes are comparable to Route 1 in their characteristics. We report the emission results for Vehicles A and C here because these provide insight into the actual on-road emissions of two Euro 3 and 4 light-commercial vehicles of category N_1. Each on-road test is conducted at least twice to detect potential data inconsistencies and malfunctioning of the PEMS equipment (see Table 3 in the Supporting Information).

Test Equipment and Parameters. PEMS have been frequently applied to heavy-duty vehicles.[16−20] Their application to light-duty vehicles is, however, relatively new.[10,21] We use a state-of-the-art Semtech-DS PEMS from Sensors Inc., which consists of a tail-pipe attachment, heated exhaust lines, an exhaust flow meter, exhaust gas analyzers, a data logger to the vehicle network, a GPS, and a weather station with sensors for ambient temperature and humidity. The main components of the Semtech-DS PEMS are installed in the cabin of the vehicles; the exhaust flow meter, GPS, and weather station are installed outside of the vehicles. The power for the Semtech-DS PEMS is supplied by external batteries to avoid interference with the engine operation while enabling PEMS testing for up to 2.5 hours. The exhaust flow meter is equipped with differential pressure devices and thermocouples that determine the exhaust mass flow based on the pitot-tube principle. With the Semtech-DS PEMS, we measure the exhaust gas concentrations of (i) THC by a heated flame ionization detector, CO and CO_2 by a nondispersive infrared sensor, and NO and NO_2 by a nondispersive ultraviolet sensor. The NO_X concentration in the exhaust gas is calculated as the sum of the NO and NO_2 concentrations. PEMS calculates the distance-specific mass of emissions based on (i) the exhaust mass flow as recorded by the exhaust flow meter and (ii) the vehicle speed as recorded by a Global Positioning System (GPS) or the engine control unit. We uniformly report on-road NO_X emissions that are uncorrected for ambient air humidity. This practice differs from the official type approval procedure in which humidity corrections are prescribed;[22] our approach is, however, justified because we aim at reporting on-road emissions as they occur under real-world driving conditions. We record emissions with PEMS using a time resolution of one second; we include cranking and cold-start emissions and we refrain from preconditioning the test vehicles.

Data Analysis. We analyze all emissions and GPS data with EMROAD, which is an Excel tool developed for extracting and processing the raw data recorded by PEMS.[23] We use EMROAD to express the on-road emissions of light-duty vehicles in line with the European emissions legislation[2] as grams per kilometer. In addition, we express emissions as dimensionless deviation ratios that provide an indication of the deviation between on-road emissions and the Euro 3−5 emission limits. The on-road emissions are presented as

(i) route averages,
(ii) averages, calculated over so-called *averaging windows* that represent subtrips of test routes and that enable a more detailed insight into the variability of on-road emissions,
(iii) cold-start emissions that comprise the emissions during the first 300 seconds of each PEMS test.

We define deviation ratios (DR) here as

$$\mathrm{DR} = \frac{m \times s_{NEDC}}{s \times m_L} \quad (1)$$

where m represents the cumulative mass of the respective pollutant [g] emitted during the averaging period, s stands for the actual distance [km] traveled during one averaging period, m_L represents the cumulative mass of the respective pollutant [g] emitted during NEDC emissions testing in the laboratory

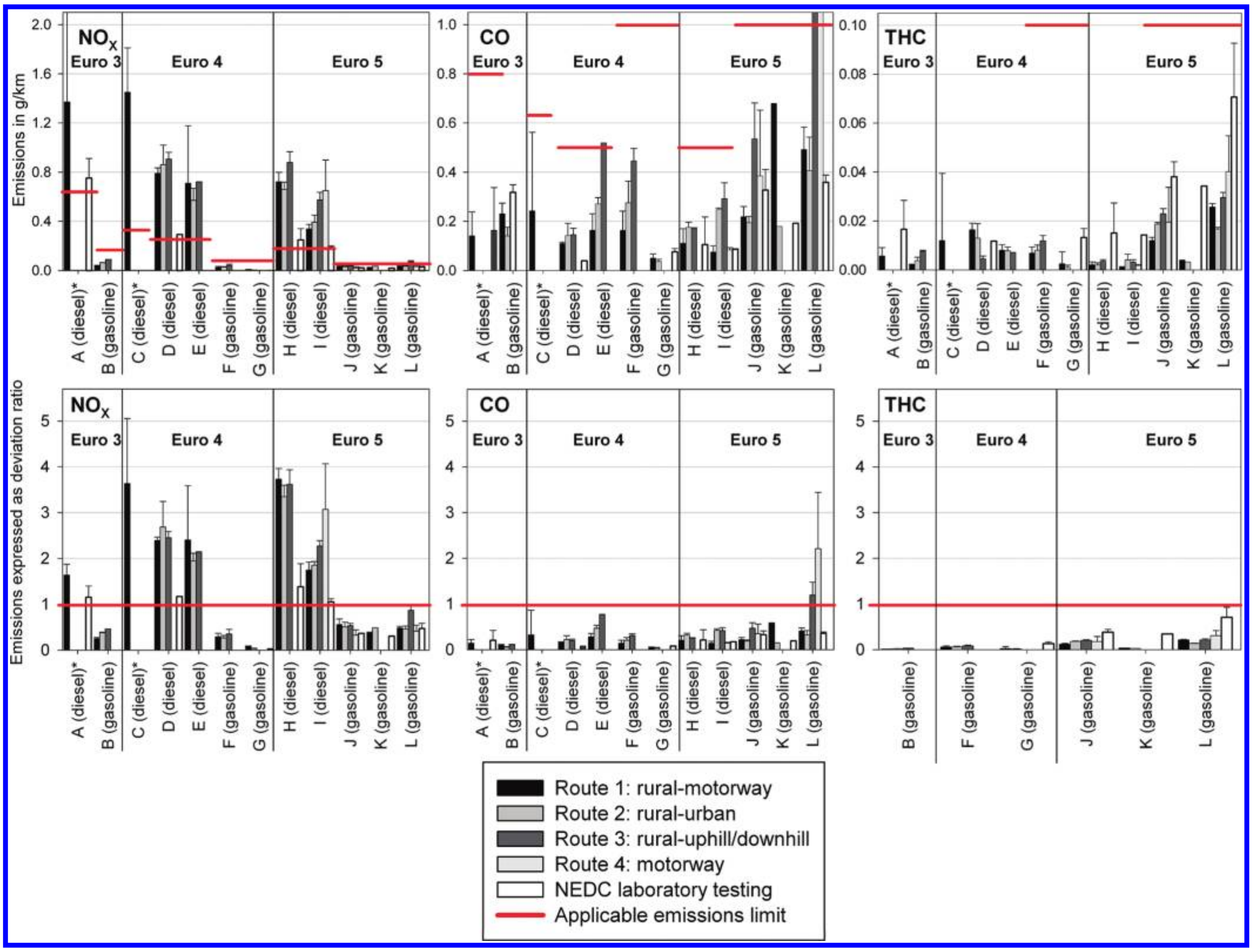

Figure 1. Route-average on-road emissions as established with PEMS and emissions as measured during laboratory testing based on the NEDC; uncertainty intervals represent the maximum emissions for each route and vehicle; the Euro 3 CO and THC emission limits for passenger cars refer to 2.3 g/km and 0.2 g/km, respectively, and are not shown here; CO emissions of Vehicle L on Routes 3 and 4 substantially exceed the Euro 5 emissions limit and reach up to 1.9 g/km and 4.5 g/km, respectively.

according to the respective Euro 3−5 emission limits, and s_{NEDC} stands for the distance of the NEDC i.e., 11.007 km.

Along with the average emissions of each vehicle on each test route, we also present the maximum emissions of each vehicle on each test route; this information is most useful for addressing air quality objectives. To calculate average emissions over individual subtrips, i.e., *averaging windows*,[20] we need to determine the distance [km] of the subtrips. We define here that subtrips shall cover exactly the distance a test vehicle needs to drive until it has emitted a cumulative mass of CO_2 [kg] that is equal to the cumulative mass of CO_2 [kg] emitted during laboratory testing with the NEDC. This way, we make reference to the type approval of light-duty vehicles. The short trips, i.e., *averaging windows* move at time increments of one second, which is equal to the sampling period of PEMS.

For representing cold-start emissions, we refrain from differentiating individual test routes because these are similar in their characteristics during the first 300 s of PEMS on-road testing. Instead, we calculate the average and maximum values for the cold-start emissions of each vehicle based on the emission measurements of all test routes.

RESULTS

The on-road CO and THC emissions of the tested light-duty vehicles generally stay below the Euro 3−5 emission limits (Figure 1). One exception presents the substantially elevated CO emissions of the Euro 5 gasoline Vehicle L during uphill-downhill and high-speed driving on Routes 3 and 4. These emissions are associated with high catalyst temperatures of up to 400 °C and point to insufficient CO oxidation that may be explained by low air-to-fuel ratios at high engine loads.

Figure 1 indicates an increase in the on-road THC emissions from Euro 3 to Euro 5 gasoline vehicles, both in absolute terms and as percentage of the respective emissions limit. Still on-road THC emissions remain below the respective emission limits.

By contrast, the route-average on-road NO_X emissions of diesel vehicles (0.93 ± 0.39 g/km), including modern Euro 5 diesel vehicles (0.62 ± 0.19 g/km), exceed emission limits by 320 ± 90%. The Euro 3−5 diesel vehicles thereby substantially exceed the established emission limit for the sum of NO_X and THC emissions. These results confirm and extend the findings of Pelkmans and Debal[8] and Vojtisek-Lom et al.,[10] who reported elevated on-road NO_X emissions of five Euro 3−4 light-duty diesel vehicles. Our results suggest that no reasonable decline in the on-road NO_X emissions from Euro 3 to Euro 5 diesel vehicles has been achieved in the past decade. The NO_X emissions of gasoline vehicles (0.03 ± 0.02 g/km) generally stay within the Euro 3−5 emission limits (Figure 1).

Among NO_X emissions, NO_2 is of particular interest because of its adverse effects on human health. We find that the share of NO_2 on the route-average NO_X emissions amounts to 48 ± 9% for diesel vehicles and 5 ± 8% for gasoline vehicles. These results are similar to the outcome of earlier laboratory tests of Euro 2−4 diesel and gasoline vehicles[24−26] as well as of recent on-road emission tests in Germany.[27] The limited sample size and relatively large variability of results precludes us, however, from identifying an increase in the share of NO_2 in the NO_X emissions of Euro 3 to Euro 5 vehicles as reported by Dünnebeil et al.[26]

The route-average on-road CO_2 emissions of all tested passenger cars amount to 160 ± 22 g/km (Figure 2). Diesel cars emit 157 ± 8 g CO_2/km and gasoline cars emit 162 ± 29 g CO_2/km. The tested passenger cars thereby exceed during on-road driving the future fleet-average performance requirements[13] by 31 ± 20%. In addition, the route-average on-road CO_2 emissions exceed the type approval emission values by 21 ± 9%; diesel and gasoline vehicles show similar deviations of 24 ± 8% and 18 ± 10%, respectively.

A more detailed insight into the variability of on-road emissions can be obtained by averaging emissions over shorter subtrips, i.e., the so-called averaging windows. Figure 3 indicates that the NO_X emissions of all averaging windows for Euro 5 diesel Vehicle H and of at least 79% of the averaging windows for Euro 5 diesel Vehicle I exceed the Euro 5 emission limit. The on-road emissions of Euro 5 diesel vehicles H in several cases exceed those of Euro 4 vehicles.

Specifically, driving at high engine loads, e.g., during uphill driving (Route 3) and at high speeds on the motorway (Route 4), results in elevated NO_X emissions. This finding can be explained by deficient exhaust gas recirculation, thus insufficient NO_X removal from the exhaust gas stream. Roughly 20% of the averaging windows on Routes 3 and 4 show NO_X emissions that exceed the Euro 5 limit by more than 8 times.

Among all on-road driving events, cold start emissions are most critical because these substantially exceed the average on-road emissions while predominantly occurring in urban areas. The results for both diesel and gasoline vehicles indicate that on-road cold-start emissions exceed the Euro 3−5 limits by 270 ± 135% for NO_X, 115 ± 51% for CO, and 47 ± 21% for THC. The cold-start emissions show no decline from Euro 3 to Euro 5 diesel and gasoline vehicles and span a large range for individual vehicles. Typically, emissions are higher during cold start than during average on-road driving because catalyst temperatures are low, causing a low efficiency in the oxidation of CO and THC as well as in the reduction of NO_X. The concentration of NO_X in the exhaust of diesel vehicles is commonly controlled by exhaust gas recirculation and exhibits a weaker temperature dependence.

DISCUSSION

This paper shows that the on-road NO_X emissions of diesel vehicles substantially exceed the Euro 3−5 emission limits. We regard this finding robust albeit associated with limitations.

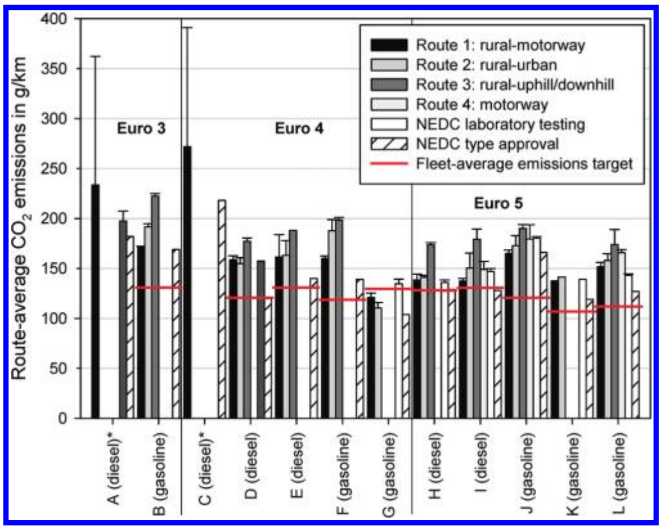

Figure 2. Route-average on-road CO_2 emissions as established with PEMS and emissions as measured during laboratory testing based on the NEDC; uncertainty intervals indicate the maximum emissions for each test route and vehicle; the future fleet-average CO_2 emissions target varies depending on the vehicle weight (see ref 13); vehicles A and C represent light-commercial vehicles for which no emissions target is defined.[13]

All test vehicles have been type approved and are subject to established durability requirements.[2] The selected vehicles are therefore suitable for identifying whether the on-road emissions of light-duty vehicles exceed emission levels as established during type approval in the laboratory. Our results do not, however, represent the average on-road emissions of light-duty vehicles in Europe for two reasons:

(i) The fleet of test vehicles is relatively small and excludes, e.g., midsize and full-size luxury cars, sport-utility vehicles, and a range of small commercial vehicles.

(ii) The test routes comprise driving on public motorways as well as national, regional, and local roads. The routes are selected to cover a wide range of driving patterns but not to represent the average European driving. A preliminary data comparison reveals that the average vehicle speed on our test routes reaches 50 ± 17 km/h while the average idling shares account for 8 ± 3%. These two parameters are well in range with the European driving data used for the development of the new Worldwide harmonized Light-duty Test Cycle (WLTC; i.e., 51 km/h and 13%, respectively).[28]

The data sets for several test vehicles are partially incomplete because not all vehicles are tested on all four test routes. This limitation is justified given practical and financial constraints of on-road emissions testing in general.

The Semtech-DS PEMS used here fulfills the requirements regarding, e.g., accuracy and linearity as specified for type approval emissions testing in the USA and EU, being now comparable to the accuracy of conventional laboratory equipment.[17,20,29] Rubino et al.[30] compared the emission measurements obtained with the Semtech-DS PEMS and standard laboratory equipment based on the NEDC and a custom-made driving cycle. Their results indicate that laboratory equipment yields 50 ± 20% lower THC emissions, 60 ± 2% lower CO emissions, and 4 ± 4% lower CO_2 emissions, whereas the values for NO_X emissions were identical given the uncertainty intervals

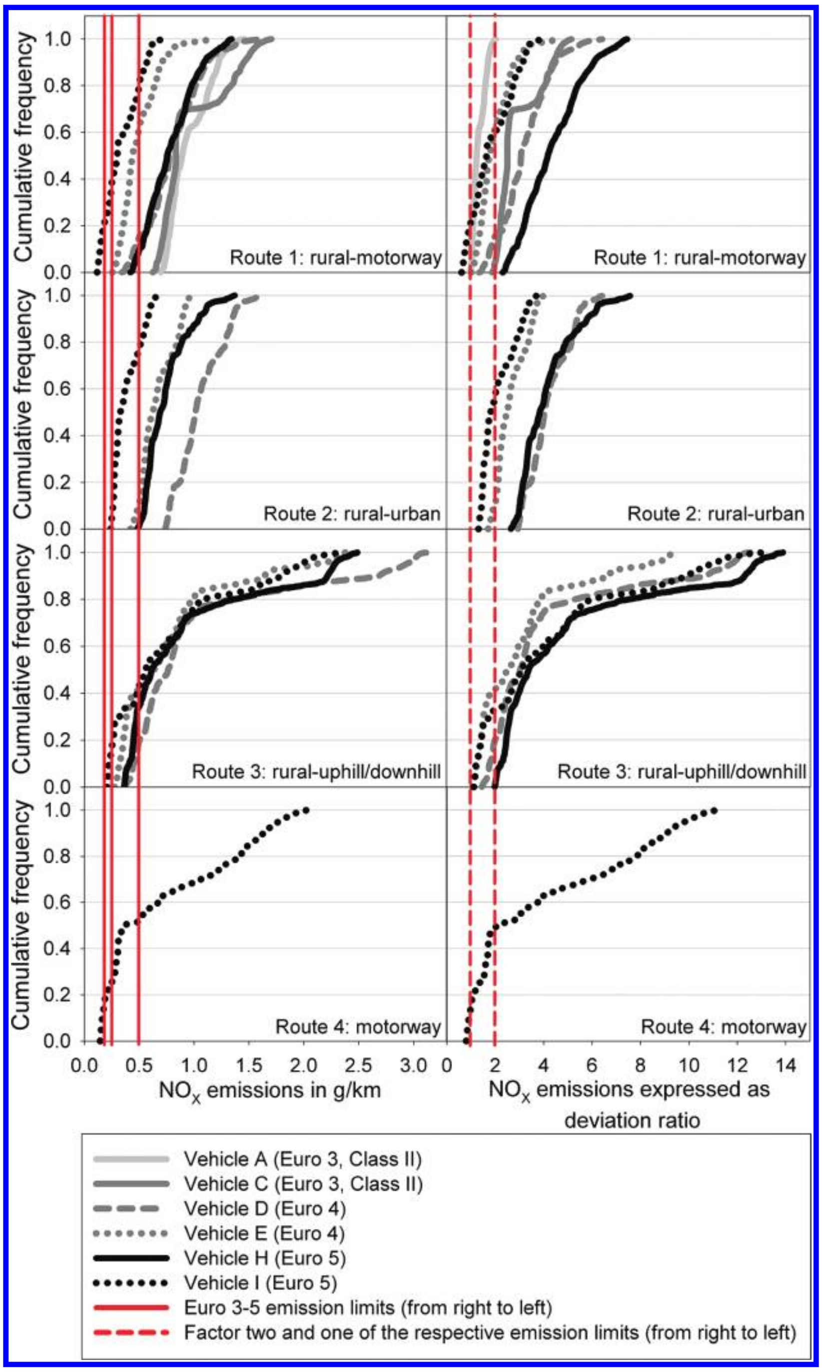

Figure 3. Averaging window NO_X emissions of Euro 3−5 diesel vehicles; vertical red lines indicate from right to left the Euro 3−5 emission limits; Euro 3−4 Class II emission limits for Vehicles A and C are not indicated; vertical red dotted lines indicate from right to left the factors two and one of the respective Euro 3−5 emission limits.

of the analytical equipment. The high relative deviations for THC and CO refer to low emission levels and are likely to become smaller if emissions increase, e.g., beyond the respective emission limits. These findings indicate the uncertainty of the PEMS measurements is limited and justifiable given the scope of this research. Relevant for the established on-road emission levels is the weight of the PEMS system, which amounts to 170 kg (kg) and thus accounts, together with a codriver weighing 75 kg, for up to 22 ± 4% of the weight of the test vehicles. The PEMS equipment may, therefore, be regarded as intrusive with respect to standard laboratory emissions testing. However, PEMS can be considered nonintrusive with respect to our objective of measuring on-road emissions during normal vehicle use that often includes the transport of several persons, vacation luggage, and sports equipment.

Our approach to report NO_X emissions that are uncorrected for the variability in air humidity is justified because we intend to capture on-road emissions as they occur under the wide range of on-road driving conditions. Furthermore, applying the standard humidity correction is only valid within the narrow specifications of laboratory testing.[22] Still, if we correct our PEMS emission values for the variability in ambient humidity, we find that humidity-corrected on-road NO_X emissions are on average 7 ± 5% lower than the uncorrected values. Humidity correction is thus negligible with respect to the outcome of this research. On a related note, the reported shares of NO_2 for gasoline vehicles are uncertain because the recorded on-road NO and NO_2 emissions are extremely low, i.e., in range of the resolution of the PEMS equipment.

PEMS have recently experienced a remarkable development, resulting in a substantial reduction of size, weight, and response time as well as in an increased accuracy. The new generation of modular PEMS equipment allows expanding applications from heavy-duty vehicles[18,20,31,32] to light-duty vehicles, including micropassenger cars. The application of PEMS to light-duty vehicles is relatively new and still partial; future test campaigns should successively cover the full range of engine technologies, after-treatment systems, and fuels.

Our results are directly applied to two areas of emissions control. First, the PEMS measurements have been used for validating emission factors applied in emission models for the transport sector, e.g., the European COPERT (COmputer Programme to calculate Emissions from Road Transport[33,34]). The results for Vehicles B, D, F, and H suggests that COPERT may overestimate on-road emissions from gasoline vehicles but underestimate NO_X emissions of Euro 4−5 diesel vehicles by up to 60%.[33] Although these findings may not be representative for the entire vehicle fleet in the EU, they can support the establishment of more reliable projections regarding the impact of stricter emission limits on (i) the actual on-road emissions of light-duty vehicles and thus (ii) the overall air quality.[35]

Second, our results provide the empirical basis for the further development of the European type approval procedure for light-duty vehicles.[2] The European Commission currently participates in the development of a World-wide harmonized Light-duty Test Cycle (WLTC) and establishes a complementary test procedure for the type approval of light-duty vehicles. This procedure should prevent potential cycle detection and cycle beating and thereby effectively limit vehicle emissions under a wide range of on-road operating conditions. To achieve this objective, the complementary test procedure must introduce a high degree of randomness into emissions testing and cover polluting driving conditions such as

(i) transient vehicle operation that cause a time lag in closed-loop emissions control in gasoline vehicles
(ii) high engine loads, which cause over fueling at full throttle and poor combustion, while limiting exhaust gas recirculation (EGR) in diesel vehicles
(iii) low exhaust gas temperatures during idling, low-load operation, and low-temperature operation that cause a low efficiency of catalytic converters (e.g., three-way catalysts in gasoline vehicles or selective catalytic reduction (SCR) catalysts in diesel vehicles[10,36])

The European Commission evaluates until the end of 2011 two candidate procedures: (i) a random laboratory driving cycle and (ii) on-road emissions testing with PEMS. We have shown that emissions testing with PEMS offers several strengths, including the ability to capture a wide range of on-road operating conditions, introduce randomness, and effectively test emissions of novel hybrid-electric vehicles. PEMS are, however, currently not yet able to measure the particle mass and particle number in the exhaust of light-duty vehicles.

Introducing the WLTC together with a complementary emissions test procedure and more stringent Euro 6 emission limits in 2014 may substantially reduce the on-road emissions of new light-duty vehicles. To achieve this objective, vehicle manufacturers may need to

(i) adapt the operation of engines (e.g., decreasing compression ratios, enabling low-temperature combustion and exhaust gas recirculation, deploying advanced fuel injection systems, and combustion control)
(ii) adopt additional exhaust after-treatment technologies (e.g., selective catalytic reduction, lean NO_X absorbers and traps, as well as particle filters for vehicles equipped with diesel engines and direct injection gasoline engines)

The required technologies are either mature or in a stage of advanced pilot testing. The costs associated with their introduction will be small compared to the overall manufacturing costs of vehicles[37,38] and can be expected to decline even further due to economies of scale and technological learning.[39] The European Commission's policy of making light-duty vehicles cleaner can accelerate the large-scale diffusion of novel emission abatement technologies, reinforce innovation in the automotive industry,[40,41] and ultimately improve the urban air quality throughout Europe.

■ ASSOCIATED CONTENT

S Supporting Information. Information on the currently applicable Euro 5 emission limits, the NEDC driving cycle, the key characteristics of PEMS test routes and equipment, and the test vehicles. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author
*Phone: +39-0332-78-6649. E-mail: martin.weiss@jrc.ec.europa.eu.

■ ACKNOWLEDGMENT

The views expressed here are purely those of the authors and may not, under any circumstances, be regarded as an official position of the European Commission. We thank Alexandra Newman (Colorado School of Mines, USA), Armistead G. Russell (Georgia Institute of Technology, USA), Juliana Stropp (Utrecht University, The Netherlands), and three anonymous reviewers for their comments on earlier drafts of this paper.

■ REFERENCES

(1) Council Directive 70/156/EEC. Official Journal of the European Union L 42, 1-15.
(2) Regulation (EC) No. 715/2007. Official Journal of the European Union L 171, 1-16.
(3) Commission Regulation (EC) No. 692/2008. Official Journal of the European Union L 199, 1-135.
(4) Directive 98/69/EC. Official Journal of the European Union L 350, 1-57.
(5) Impact of selected policy measures on Europe's air quality. EEA − European Environmental Agency: EEA Report No 08/2010; Copenhagen, Denmark, 2010.
(6) *European Union emission inventory report 1990−2008 under the UNECE convention on Long-Range Transboundary Air Pollution (LRTAP)*. EEA − European Environmental Agency: EEA Technical Report No 7/2010; Copenhagen, Denmark, 2010.

(7) *Exceedance of air quality limit values in urban areas (CSI 004) - Assessment published December 2009*. EEA — European Environmental Agency: Kopenhagen, Denmark, 2009. http://www.eea.europa.eu/data-and-maps/indicators/exceedance-of-air-quality-limit1/ exceedance-of-air-quality-limit-1 (accessed October 11, 2010).

(8) Pelkmans, L.; Debal, P. Comparison of on-road emissions with emissions measured on chassis dynamometer test cycles. *Transport Res. D-Tr E.* **2006**, *11* (4), 233241; doi:10.1016/j.trd.2006.04.001.

(9) Hausberger, S.; Blassnegger, J. *Sackgasse oder Zukunft? Das motorische Potenzial beim Diesel*. AK Presentation "Welche Zukunft hat der Diesel?" Vienna, Austria, 2006.

(10) Vojtisek-Lom, M.; Fenkl, M.; Dufek, M.; Mareš, J. Off-cycle, real-world emissions of modern light duty diesel vehicles. *SAE J-Automot. Eng.* **2009**, 2009–24—0148.

(11) Directive 2001/116/EC. Official Journal of the European Communities L 18, 1-115.

(12) Directive 2001/100/EC. Official Journal of the European Communities L 16, 32-34.

(13) Regulation (EC) No. 443/2009. Official Journal of the European Union L 140, 1-15.

(14) André, M.; Pronello, C. Relative influence of acceleration and speed on emissions under actual driving conditions. *Int. J. Vehicle Des.* **1997**, *18* (3—4), 340353.

(15) Kageson, P. *Cycle-beating and the EU test cycle for cars*. European Federation for Transport and Environment: Brussels, Belgium, 1998.

(16) Tzirakis, E.; Karavalakis, G.; Schinas, P.; Korres, D.; Karonis, D.; Stournas, S.; Zannikos, F. Diesel-water emulsion emissions and performance evaluation in public buses in Attica Basin. *SAE J-Automot. Eng.* **2006**, 2006-01-3398.

(17) *Determination of PEMS measurement allowances for gaseous emissions regulated under the heavy-duty diesel engine in-use testing program*. Revised Final Report EPA420-R-08-005; EPA — United States Environmental Protection Agency: Arlington, USA, 2008.

(18) Bonnel, P.; Kubelt, J. *Heavy-duty engines conformity testing based on PEMS - Lessons learned from the European pilot program*. EUR Draft report; European Commission — DG JRC: Ispra, Italy, 2011.

(19) Regulation (EC) No. 595/2009. Official Journal of the European Union L 1888, 1-13.

(20) Draft of Commission Regulation on implementing and amending Regulation (EC) No. 595/2009 of the European Parliament and of the Council on type-approval of motor vehicles and engines with respect to emissions from heavy duty vehicles (Euro VI) and on access to vehicle repair and maintenance information. EC — European Commission, 2011. Forthcoming.

(21) Rubino, L.; Bonnel, P.; Hummel, R.; Krasenbrink, A.; Manfredi, U.; de Santi, G. On-road emissions and fuel economy of light duty vehicles using PEMS: chase-testing experiment. *SAE Int J. Fuels Lubr.* **2009**, *1* (1), 14541468.

(22) UNECE Regulation No. 83 - Rev. 4 - Emission of pollutants according to engine fuel requirements. UNECE — United Nations Economic Commission for Europe: Geneva, Switzerland, 2008. http://live.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/r083r4e.pdf (accessed January 18, 2011).

(23) Kubelt, J.; Bonnel, P. *Portable emission measurements (PEMS) - Data evaluation and post-processing manual for the data evaluation software EMROAD© - Version 4.00*. EUR Draft report; EC-JRC: Ispra, Italy, 2007.

(24) Soltic, P.; Weilenmann, M. NO_2/NO emissions of gasoline passenger cars and light-duty trucks with Euro 2 emission standard. *Atmos. Environ.* **2003**, *37* (37), 52075216; doi:10.1016/j.atmosenv.2003.05.003.

(25) Alvarez, R.; Weilenmann, M.; Favez, J.-Y. Evidence of increased mass fraction of NO_2 within real-world NO_X emissions of modern light vehicles - derived from a reliable online measuring method. *Atmos. Environ.* **2008**, *42* (19), 46994707; doi:10.1016/j.atmosenv.2008.01.046.

(26) Dünnebeil, F.; Lambrecht, U.; Kessler, C. Zukünftige Entwicklung der NO_2-Emissionen des Verkehrs und deren Auswirkung auf die NO_2-Luftbelastung in Städten in Baden-Württemberg (The traffic-realted NO_2 emissions and their impact on the air quality in cities of Baden-Württemberg). IFEU — Institut für Energie- und Umweltforschung Heidelberg gGmbH: Heidelberg, 2007. www.ifeu.de/verkehrundumwelt/pdf/IFEU_et_al%282007%29_NO2_Emission_und_Immission_in_Baden-Wuerttemberg.pdf (accessed June 21, 2011).

(27) Kleinebrahm, M; Steven, H. *Vermessung des Abgasemissionsverhaltens von zwei Pkw und einem Fahrzeug der Transporterklasse im realen Strassenbetrieb in Stuttgart mittels PEMSTechnologie* (Using PEMS for measuring the emissions of two cars and one light commercial vehicles during on-road driving in Stuttgart). Abschlussbericht. Nr. 4500116246/33. Karlsruhe.

(28) JRC. Unpublished European driving data. JRC — Joint Research Centre of the European Commission: Ispra, 2011.

(29) Final Rule Part 1065 Test Procedures - Subpart J "Field Testing" - 40 Code of Federal Regulations Part 1065. EPA — United States Environmental Protection Agency: 2008. http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=33f172b24a3dff82c1b6f6ba8b15e982&tpl=/ecfrbrowse/Title40/40cfr1065_main_02.tpl (accessed June 21, 2011).

(30) Rubino, L.; Bonnel, P.; Hummel, R.; Krasenbrink, A.; Manfredi, U.; De Santi, G.; Perotti, M.; Bomba, G. PEMS light-duty vehicles application: experiences in downtown Milan. *SAE J-Automot Eng.* **2007**, Paper Number: 2007-24-0113, 115; DOI: 10.4271/2007-24-0113.

(31) *Regulatory announcement: Proposed in-use testing program for heavy-duty diesel engines and vehicles*. United States Environmental Protection Agency: EPA420-F-04-042; Washington, DC, 2004. http://epa.gov/oms/highway-diesel/regs/420f04042.pdf (accessed June 21, 2011).

(32) Bonnel, P.; Rubino, L.; Carriero, M.; Fumagalli, I.; Kubelt, J.; Manfredi, U.; Brunella, A.; Montigny, F.; Hummel, R.; Krasenbrink, A.; De Santi, G. *European project on portable emissions measurement systems: "EU-PEMS" Project - Guide for the preparation and the execution of emissions road tests on heavy-duty vehicles*. JRC33764. European Commission — Joint Research Centre: Ispra, 2006.

(33) Kousoulidou, M.; Ntziachristos, L.; Hausberger, S.; Rexeis, M. Validation and improvement of CORINAIR's emission factors for road transport using real-world emissions measurements. LAT Report No: 10.RE.0031.V1; Thessaloniki, 2010.

(34) Kousoulidou, M. Experimental and theoretical investigation of European road transport emissions evolution with the use of conventional fuels and biofuels. Ph.D. Dissertation, Aristotle University of Thessaloniki, Thessaloniki, 2011.

(35) Giannouli, M.; Kalognomou, E.-A.; Mellios, G.; Moussiopoulos, N.; Samaras, Z. Impact of European emission control strategies on urban and local air quality. *Atmos. Environ.* **2011**; doi:10.1016/j.atmosenv.2010.03.016.

(36) Nesamani, K. S.; Chu, L.; McNally, M. G.; Jayakrishnan, R. Estimation of vehicular emissions by capturing traffic variations. *Atmos. Environ.* **2007**, *41*, 29963008; doi:10.1016/j.atmosenv.2006.12.027.

(37) Gense, N. L. J.; Jackson, N.; Samaras, Z. *Euro 5 technologies and costs for light-duty vehicles — the expert panels summary of stakeholders responses*. TNO Report 05.OR.VM.032.1/NG; TNO Science and Industry: Delft, The Netherlands, 2005.

(38) Impact assessment for Euro 6 emission limits for light-duty vehicles. Commission staff working document. EC — European Commission. Brussels, European Union, 2006.

(39) Weiss, M.; Patel, M. K.; Junginger, H. M.; Blok, K. A review of experience curve analyses for energy demand technologies. *Technol. Forecast Soc.* **2010**, *77* (3), 411428; doi:10.1016/j.techfore.2009.10.009.

(40) Porter, M. E. America's green strategy. *Sci. Am.* **1991**, *264* (4), 96.

(41) Porter, M. E.; van der Linde, C. Towards a new concept of the environment-competitive relationship. *J. Econ. Perspect.* **1995**, *9* (4), 97118.