NOx, NH3, N2O and PN real driving emissions from a Euro VI heavy-duty vehicle. Impact of regulatory on-road test conditions on emissions

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HIGHLIGHTS
• Current boundary conditions lead to underestimation of NOx emissions.
• High NOx emissions were observed in urban environments.
• PN, N2O and NH3 can be measured during on-road testing.
• Low emissions of PN and NH3 were measured during the on-road tests.
• Heavy-duty vehicles may present substantial N2O emissions.

GRAPHICAL ABSTRACT

ABSTRACT

Euro VI emission standards for heavy-duty vehicles (HDVs) introduced for the first time limits for solid particle number (PN) and NH3 emissions. EU regulation also includes a Portable Emissions Measurement System (PEMS) based test at type approval, followed by in-service conformity (ISC) testing. A comprehensive study on the real-time on-road emissions of NOx, NH3, N2O and PN from a Euro VI HDV equipped with a Diesel Oxidation Catalyst (DOC), a Diesel Particle Filter (DPF), a Selective Catalytic Reduction (SCR) system and an Ammonia Oxidation Catalyst (AMOX) is presented. Our analyses revealed that up to 85% of the NOx emissions measured during the tests performed are not taken into consideration if the boundary conditions set in the current legislation are applied. Moreover, it was found that the highest NOx emissions were measured during urban operation. Analyses show that a large fraction of urban operation is not considered when 20% power threshold as boundary condition is applied. They also show that cold start emissions account for a large fraction of the total NOx emitted. Low emissions of PN (2.8 × 1010 to 6.5 × 1010 #/kWh) and NH3 (1.0 to 2.2 ppm) were obtained during the on-road tests, suggesting effectiveness of the vehicle’s after-treatment (DPF and AMOX). Finally, a comparison between speed-based (as currently defined by Euro VI legislation) and land-use-based (using Geographic Information System (GIS)) calculation of shares of operation was performed. Results suggest that using GIS to categorize the shares of operation could result in different interpretations depending on the criteria adopted for their definition.

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1. Introduction

European air policy has made substantial progress in past decades towards reducing air pollution (EEA, 2015). Exposure of the European urban population to particle matter (PM) and to nitrogen dioxide (NO₂) has decreased. Between 2003 and 2012, nitrogen oxides (NOₓ) total emissions in EU28 (28 members of the European Union) have decreased by 43% and PM₁₀ (particulate matter with a diameter smaller than 10 μm) have been reduced by 16%. However, Europe is still far from achieving levels of air quality that do not represent a risk to human health and to the environment. Particulate matter, ground-level ozone (O₃), NOₓ, and ammonia (NH₃) are among Europe’s most problematic air pollutants (EEA, 2015). The road transport sector is considered to be an important source of NH₃ (Suarez-Bertoa et al., 2014) and a major contributor to PM and NOₓ pollution in the European cities, where population densities are higher (80% of the European population are city dwellers) (Eurostat, 2015). In order to improve the air quality, more stringent vehicle emission standards were recently introduced in Europe (e.g. heavy-duty vehicles (HDV) Euro VI emission standards were introduced in Europe in 2014; EC, 2009). The new emission standards for HDV included more stringent emission limits for hydrocarbons (HC), NOₓ, PM and for the first time included solid particle number (PN) and NH₃. The United Nations Economic Commission for Europe (UNECE) Regulation 49 (UNECE, 2013) defined the PN measurement procedure and set the limit to 6 × 10¹¹ #/kWh for Euro VI engines as measured over the world harmonized transient cycle (WHTC). Euro VI legislation (EU, 2011) includes a Portable Emissions Measurement System (PEMS) based test at type approval, followed by the in-service conformity (ISC) testing, which is devised as a measure to verify the emissions of the vehicle throughout its useful life. The PEMS test is carried out under normal driving conditions (i.e. on-road) and the trips performed have to comply with several practical boundaries (e.g. different shapes of operation and route composition, amount of work performed by the engine, etc.). This allows for a comprehensive analysis of the emissions of HDVs under normal driving conditions and provides confidence that emissions during on-road operation conform with engine certification values.

PEMS can also be a useful tool to better understand the behavior of a vehicle in different driving scenarios and with variables which are not easy to simulate in the laboratory, e.g., weather and traffic conditions, road gradient, and driving style. The importance of being able to analyze the impact of these variables on the emissions is changing emission control approaches in the automotive industry and driving the development of different technologies to better control the level of emitted pollutants in urban areas, where it matters the most in terms of human exposure.

At the moment, during PEMS on-road testing for type-approval and ISC only NOₓ, CO, and HC are measured. Other pollutants such as PN, N₂O and NH₃, which are regulated in different countries, are only measured in (laboratory) type-approval tests, NH₃ (which is a precursor of fine particle formation in the atmosphere (Kim et al., 2000; Phan et al., 2013)) and N₂O (which is a powerful greenhouse gas and the single most important ozone-depleting substance (ODS) (Ravishankara et al., 2009)) are present in HDV exhaust due the use of urea/SCR DeNOₓ systems and a Quantum Cascade Laser Infra-Red (QCL-IR; for NO, NO₂, N₂O and NH₃) and Engine Control Unit (ECU), which also provided information related to the SCR, including urea solution injection rate and pre- and post-SCR NOₓ concentrations. A PN-PEMS instrument to measure PN emissions was also used. Details of the vehicle are summarized in Table S1 and the general setup of the instrumentation in the vehicle is represented in Fig. S1. The vehicle was tested on-road using three different routes and two starting conditions (cold and hot start) for a total of four tests (see Table 1). A test is considered a hot start when the coolant temperature at the beginning of the test is T₀ ≥ 70 °C (EU, 2011).

2. Experimental

2.1. Analytical instrumentation

Real time on-road exhaust emissions from a Euro VI N3 category heavy-duty diesel vehicle equipped with a DOC, DPF, SCR and AMOX were studied. The measurements were performed using PEMS (for NOₓ, CO and CO₂), global positioning system (GPS), data acquisition and a Quantum Cascade Laser Infra-Red (QCL-IR; for NO, NO₂, N₂O and NH₃) and Engine Control Unit (ECU), which also provided information related to the SCR, including urea solution injection rate and pre- and post-SCR NOₓ concentrations. A PN-PEMS instrument to measure PN emissions was also used. Details of the vehicle are summarized in Table S1 and the general setup of the instrumentation in the vehicle is represented in Fig. S1. The vehicle was tested on-road using three different routes and two starting conditions (cold and hot start) for a total of four tests (see Table 1). A test is considered a hot start when the coolant temperature at the beginning of the test is T₀ ≥ 70 °C (EU, 2011).

2.1.1. Portable Emissions Measurements System (PEMS)

The PEMS equipment used was the Semtech-DS, which consists of tailpipe attachment, heated exhaust lines, exhaust flow meter (EFM), exhaust gas analyzers, data logger from vehicle network, GPS and a weather station (WS) for measuring ambient temperature and humidity. All data were recorded at a frequency of 1 Hz. The whole system (instrument and battery) adds a further ~100 kg of instrumentation to the vehicle besides the weight of the driver (~80 kg). The Semtech-DS measured exhaust gas concentrations of carbon monoxide (CO) and carbon dioxide (CO₂) by a non-dispersive infrared sensor, and nitrogen monoxide (NO) and nitrogen dioxide (NO₂) by a non-dispersive ultraviolet sensor. NOₓ mass emissions were calculated using the sum of the concentrations of NO and NO₂ and the density of NO₂ (see EU, 2011). The EFM uses a Pitot tube based on Bernoulli’s principle in order to calculate mass flow on the basis of airflow differential pressure measurement. As a standard procedure, test runs preparation included routine calibration of pollutant analyzers (zero and span of gases). Vehicle exhaust temperature was measured on the tailpipe.

2.1.2. Quantum Cascade Laser Infra-Red Spectrometer

The MEKA 1400QIL-NX is an analyzer that simultaneously measures four nitrogen compounds (NO, NO₂, N₂O, NH₃) in automobile exhaust

| Table 1 | Trips characteristics for Tests 1–4. Work is equal to the amount of times the WHTC work has been performed along the trip. |
|---------|----------------------------------------------------------------------------------------------------------------------------------|
| Test    | Test 1 | Test 2 | Test 3 | Test 4 |
| Work (× WHTC) | 3.7 | 3.7 | 3.1 | 3.0 |
| Urban share [%] | 46 | 48 | 56 | 62 |
| Rural share [%] | 18 | 17 | 22 | 24 |
| Motorway [%] | 36 | 35 | 22 | 14 |
| Cold start | Yes | Yes | No | No |
| Trip duration [s] | 10,382 | 10,712 | 9279 | 11,354 |
| Trip distance [km] | 154.8 | 154.8 | 123.3 | 132.9 |
| Ambient temperature [°C] | 11 | 18 | 12 | 16 |
gas in real time by using Infrared Absorption Spectroscopy. The instrument combines a Quantum Cascade Laser (QCL) light source and a precisely adjusted long dual-path optical cell. The QCL has a wide dynamic range (i.e., 0–50 ppm to 0–2000 ppm) for the measurement of ammonia emissions in the exhaust gas. The MEXA 1400 QL-NX has a wavelength resolution close to 0.006 cm⁻¹. Further details on the instrument and its performance during the real time measurements of NH₃ emission on transient cycles and correlation between this instrument and a FTIR can be found in Suarez-Bertoa et al. (2015, 2016).

2.1.3. PN instrumentation

The PN instrument used to measure (solid) PN emissions was the ViPR from Testo, compliant with UNECE Regulation 49. The instrument consists of a hot (150 °C) dilutor, an evaporation tube at 350 °C, a secondary dilutor at ambient temperature and a condensation particle counter (CPC; TSI 3790) with particle diameter cut-off of 23 nm (dₛ₅₀ = 23). The Particle number Concentration Reduction Factor (PCRF) chosen was 540 (primary 110 and secondary 4). A 2 m sampling line (conductive Teflon) heated at 100 °C was used to connect the primary diluter to the tailpipe of the vehicle (sampling rate 1.5 l/min and residence time approximately 3 s).

2.2. Route description

Table 1 shows the characteristics of the trips examined in this study. The different routes contain a larger percentage of urban operation compared to the rural and motorway shares and all the trips considered for the analysis have performed between 3 and 3.7 times the amount of work produced over the WHTC applicable to the engine used by the vehicle.

Tests 1 and 2 are similar trips with cold start used to evaluate to what extent cold start emissions impact the final result. Tests 3 and 4 were performed using different routes where urban operation was prevalent.

GPS measurements of Test 4 were imported in the GIS environment, where the geoprocessing of the real time on-road data from PEMS test were performed using ArcGIS 10.0. The aim of GIS analysis was to assess different boundary conditions for the PEMS test execution. Two criteria were assessed: The land use and the road speed-limits.

2.3. Data analysis

2.3.1. Moving Averaging Window (MAW) method for data analysis

The moving averaging window method (EU, 2011; Suarez-Bertoa et al., 2016; Perujo Mateos Del Parque and Mendoza Villafuerte, 2015) is an averaging process, based on a reference quantity obtained from the engine characteristics and its performance on the type approval transient cycle (i.e., for Euro VI – the amount of work produced over the WHTC or the mass of CO₂ emitted over a WHTC). The reference quantity sets the characteristics of the averaging process (i.e. the duration of the windows). Using the MAW method, the pollutant emissions are integrated over windows whose common characteristic is the reference engine work or CO₂ mass emissions.

Using the engine work or CO₂ mass over a fixed cycle (i.e. WHTC) as reference quantity is an essential feature of the method, leading to the same level of averaging and range of results for various engines. The first window is obtained between the first data point and the data point for which the reference quantity (1 × CO₂ or work achieved at the WHTC) is reached. The calculation is then repeated for subsequent data points, with a time increment equal to the data sampling frequency (at least 1 Hz for the gaseous emissions).

Emission factors (EFs) are then calculated by dividing the integrated emissions by the work of the window (i.e. WHTC work). Results reported in this study include NOₓ, PN, NH₃, and N₂O. During ISC the vehicle should comply with a conformity factor of 1.5 for the NOₓ emissions (i.e., 1.5 times Euro VI NOₓ limits; 0.69 g/kWh). There are no defined on-road limits for PN and NH₃, so WHTC limits were applied (6 × 10¹¹ #/kWh and 10 ppm, respectively). The same MAW approach was followed to analyze the instantaneous PN emissions to be consistent with the methodology. On the other hand, NH₃ emissions are regulated as average concentration over the type approval cycle (ppm/test) (UN/ECE, 2013). Hence, NH₃ emissions were reported as average concentration (ppm) over the MAW, but also as EF (g/kWh), similarly to the other studied compounds.

2.3.2. EMROAD data evaluation tool

Data from the PEMS based testing was analyzed using EMROAD V5.80. EMROAD (Bonnel et al., 2011; Bonnel, 2015) is a Microsoft Excel add-in used to analyze on-road emissions data collected with PEMS. It was developed as a calculation tool to support the data analysis in the frame of the European legislative pilot-programs developing PEMS based testing (heavy-duty, non-road engines and light-duty vehicles). EMROAD is used to support the development of new PEMS data evaluation methods for emissions legislation such as the ISC (heavy-duty and non-road engines) and real driving emissions (RDE, light-duty vehicles).

2.3.3. Boundary conditions for data evaluation

The current PEMS procedure for heavy-duty vehicles is defined by a series of boundary conditions that prescribes the amount of data to be taken into consideration for the final emissions analysis. They are the following:

   i. Vehicle/engine conditioning: Cold start emissions data is not taken into account. The data evaluation starts after the engine coolant temperature has reached 70 °C for the first time or after the coolant temperature is stabilized within ±2 K over a period of 5 min (whichever comes first but not later than 20 min after engine starts).

   ii. More than 50% of the total available MAW windows must be valid; the validity of the windows is prescribed by the percentage of averaged engine power operation: The windows whose average power is below 20% (or 15%, if 50% of the total of windows is not achieved, it is possible to lower the threshold up to 15% to achieve the percentage of windows required for the analysis) of the maximum indicated engine power are not considered.

   iii. 90th cumulative percentile of the MAW EF as the representative result of the vehicle instead of the maximum EF (which would represent the worst polluting “window”). 90th cumulative percentile boundary has been implemented in the regulation to prevent the inclusion of outliers which would not be representative of the emission performance of the vehicle during a trip.

The amount of data use during the analysis may result in different emissions factors. Hence, four different methods (baseline, Methods 1–3) were applied to evaluate to which extent the regulatory boundary conditions could alter the emission factors. Moreover, Method 4 was used to study the emissions according to the different average speed of the windows. Hence, the process followed to analyze the data from each test was the following:

   a) Baseline: Obtain emissions factors following the methodology as described in the legislation (considering all boundary conditions) in order to establish a baseline. (namely, cold start is excluded, only windows with power ≥ 20% and 90th cumulative percentage)

   b) Method 1 – Includes the cold start operation of those trips which started with the engine cold.

   c) Method 2 – Includes cold start and no power threshold, but still uses the 90th cumulative percentile.

   d) Method 3 – Includes all collected data and uses 100th cumulative percentile.
e) Method 4 – Binning of the MAW emissions factors according to the average speed of all instantaneous data in the window into urban (<50 km/h), rural (50–75 km/h) and motorway (>75 km/h). The binning is performed using all MAW without boundaries and data considered are the maximum obtained values (100th cumulative percentile). This method is performed to show the impact of the driving operation (urban, rural or motorway) on the emissions, given that this is also representative of the usage of the engine power.

2.3.4. GIS analysis

##### 2.3.4.1. Land-use-based boundaries.

The CORINE Land Cover (CLC) map is the European reference for land use. Developed and updated by the European Environmental Agency (EEA), under the CORINE (Coordination of information on the environment) program, it classifies most European territory in 44 land use classes (SIA, 2000).

The most recent and validated CLC map (CLC 2006 (EEA, 2006)) was used to identify urban and rural areas covered by Test 4 route, with the purpose of defining urban and rural shares of operation, from a land-use perspective.

A re-classification of CLC classes was applied to produce the urban-rural map of the Test 4 areas: Urban areas include all the CLC artificial surfaces (namely continuous and discontinuous urban fabric, industrial and commercial units, construction sites, green urban areas and sport-leisure facilities), while rural areas group all the elements inventoried by CLC as agricultural, or forest and semi-natural land use. Wetlands and Water classes were excluded from the analysis. The CLC inventory does not consider transport network as a land use class, but includes it in the artificial surfaces.

##### 2.3.4.2. Speed-limits based boundaries.

Current speed limit policies differ between countries and a harmonized reference does not exist at European level. In Italy speed limits (i.e. the maximum speed allowed by law) are set by the Highway Code (L. D. n. 285/1992 (MIT, n.d.)) according to road and vehicle type.

### Table 2

| NOx emissions (g/kWh) obtained applying Baseline and Methods 1–3 for data analysis. NH₃ emission concentration (ppm) and NH₃, NOx, EFs emission factors (mg/kWh) and PN emission concentration (#/kWh) analyzed applying Method 3 (i.e., MAW analysis including all data). |
|---|---|---|---|---|
| **Test 1** | **Test 2** | **Test 3** | **Test 4** |
| NOx, baseline [a] [g/kWh] | 0.17 | 0.30 | 0.62 | - |
| NOx, method 1 [b] [g/kWh] | 0.18 | 0.30 | 0.62 | - |
| NOx, method 2 [c] [g/kWh] | 0.46 | 0.45 | 0.62 | 2.37 |
| NOx, method 3 [d] [g/kWh] | 1.15 | 1.60 | 1.14 | 2.39 |
| NH₃ [ppm] | Max 3.8 | 4.7 | 1.8 | 1.4 |
| Min | 0.4 | 0.4 | 0.4 | 0.3 |
| Average | 2.2 | 2.0 | 1.1 | 1.0 |
| NOx, method 2’ [e] [g/kWh] | Max 5 | 4 | 6 | 3 |
| Min | 19 | 18 | 9 | 9 |
| Average | 38 | 35 | 27 | 26 |
| N₂O [mg/kWh] | Max 83 | 85 | 77 | 62 |
| Min | 41 | 48 | 52 | 36 |
| Average | 67 | 70 | 66 | 50 |
| PN [#/kWh] | Max | 3.8 × 10¹⁰ | NA | 5.3 × 10¹⁰ | 7.4 × 10¹⁰ |
| Min | 2.2 × 10¹⁰ | NA | 2.0 × 10¹⁰ | 5.1 × 10¹⁰ |
| Average | 2.8 × 10¹⁰ | NA | 4.0 × 10¹⁰ | 6.5 × 1⁰¹⁰ |

[a] Baseline [CS excluded, 90th %ile, 20% PT].
[b] Method 1 [Cold start (CS) included, 90th %ile, 20% power threshold (PT)].
[c] Method 2 [CS included, 90th %ile, No PT].
[d] Method 3 [all recorded data].
[e] Not enough MAW to be able to have a valid test EF based on boundary conditions.

### 3. Results and discussion

Real time emissions from a Euro VI compression ignition HDV were measured using the Sentech-DS and a QCL-IR during 2 cold start (Test 1 and Test 2) and 2 hot start (Test 3 and Test 4) on-road tests (see Table 1). PN measurements were performed during Test 1, Test 3 and Test 4 using a ViPR.

#### 3.1. Boundaries of data analysis and their effect on reported NOx emissions

Table 2 shows the NOx emissions following the different methods. The EFs obtained vary depending on the excluded boundaries and trip shares of operation. NOx EFs from this vehicle considering all trips and conditions range from 0.17 (Test 1 and Baseline analysis, i.e., cold start is excluded, only windows with power ≥ 20% and 90th cumulative percentage) to 2.39 g/kWh (Test 4 Method 3, i.e., including all the data measured during the test), where the Euro VI emission limit for NOx is 0.46 g/kWh. Previous tests conducted on similar routes with a Euro V N3 category truck showed NOx emissions ranging between 6.23 and 11.48 g/kWh (Suárez-Bertoa et al., 2016). Looking at the variation within a single test it can be seen that NOx emission factors were 1.8 times (Test 3) to 6.8 times (Test 1) higher when all available data were taken into consideration – method 3 – compare to emission factors obtained when all the boundaries were considered – baseline – (see Table 2). Vehicles emissions are higher during cold start due to the effect of the thermal efficiency of the engines, which is lower at cold start than when the vehicle reaches steady state temperatures owing to sub-optimal lubricant and component temperatures (Roberts et al., 2014). Also, since catalytic converters require a certain temperature (typically above 200 °C) to work to full efficiency, emissions are higher during the warm up period (Guan et al., 2014). After few minutes of vehicle operation, both the engine coolant and the catalytic converter have generally warmed, and emissions are significantly lower. This effect lasts several minutes after the engine is shut off (Reiter and Kockelman, 2016). For these reasons, larger differences were observed for Test 1 and 2, cold start tests (engine coolant temperature, Tcool < 70 °C), than Test 3, which was a hot start test (Tcool > 70 °C).

Fig. 1a shows the second-by-second NOx emissions of Test 2 to place these increments in context. The red dotted line separates the emissions produced during the cold start (Tcool < 70 °C). These cold start emissions represented 63.4% of the total NOx mass emitted during the whole trip and these emissions are excluded from the final analysis because of the imposed boundary conditions; in this case exclusion of cold start emissions and in a larger extent 90th cumulative percentile (see Table 2). Fig. 1b shows the distribution of the cold and warm operation mass emissions vs power in second-by-second data. The instantaneous data shows that NOx emissions are highest at high power when the engine is cold. When the engine is cold and the vehicle has just started the trip, the state of the after-treatment is also critical as the exhaust has not yet reached a temperature that allows the after-treatment to work efficiently. On the other hand, in Fig. 2a, the vehicle shows high emissions under urban conditions after a period of motorway operation (high speed, high power and high exhaust temperatures). This high emissions period suggests that exhaust temperature is not the only ruling parameter for an effective behavior of the after-treatment system. High emission factors are also evident when the results are processed within the MAW analysis.

Fig. 1c shows the distribution, in g/kWh, of the emissions of each MAW vs the average power of the window. As it can be seen, the power threshold boundary containing the highest reported emissions per MAW is not considered in the analysis with the current regulatory method. Further to this, the 90th cumulative percentile boundary restricts even more the data as it is applied into the already limited data. Hence, the value of emissions reported for the baseline of Test 2 in Fig. 1 is of 0.30 g/kWh, but it rises to 1.60 g/kWh (>5 times higher) when no boundaries are applied.
Test 4 reports no emissions at both baseline and method 1 analysis (see Table 2) because the required number of valid windows above the 20% (15%) power threshold was not achieved. Test 4 has the highest percent of urban operation (see Table 1). The test was designed to include a preconditioning of the vehicle and after-treatment system during the first part of the trip by by first undertaking a prolonged motorway run prior to entering the urban operation. This was intentionally done to investigate the behavior of this vehicle under a “normal/everyday usage pattern, where the vehicle departs from a rural location and takes its load to the city and then back.

NOx emissions were significantly higher in Test 4 (2.39 g/kWh) than in the other tests as the result of higher NOx emissions during urban operation. While the urban share of Tests 1–3 were mainly driven on a road with very little traffic, roundabouts and traffic lights, most parts of the urban share of Test 4 were performed in a city (Fig. 2 at ~5000 s) and a large town (Fig. 2 at ~9000 s). Driving in congested (or more dynamic) environments led to more frequent stop/start events, where most of the NOx emissions took place (see Fig. 1a and Fig. 2).

Furthermore, even if the engine was at the optimum working conditions after > 1 h of operation (motorway), no injection of urea solution was registered while operating in the city/town. As a consequence, NOx emissions were the highest measured during the trip.

Urea injection did not happen during the cold start of any of the studied trips. This could be expected as the temperature of the catalytic converter would be insufficient for dissociation of urea to NH3. Once the vehicle coolant temperature reached 70 °C, and constant cruise speeds were achieved, urea solution was injected and NOx emissions were relatively low, even in the urban operation (i.e., speed < 50 km/h).

Fig. 3a illustrates the relation between NOx emissions and engine power at low and high speed during Test 4. As it can be seen, higher emissions were prone to happen at low vehicle speeds regardless of the percent of maximum power the engine was producing. Driving dynamics of the trip will have an effect on the power produced by the engine, as low/high vehicle speeds will require a different amount of energy to move the vehicle and its payload. When this energy varies, it affects directly the engine out gas temperature which in turn affects

![Fig. 1. (a) Instantaneous NOx emissions measured during Test 2; (b) instantaneous cold/warm operation NOx emissions vs % of maximum power; (c) MAW based emissions vs MAW average power during Test 2.](image-url)
the after-treatment temperature. Quickly accelerating the vehicle requires instant power of the engine for a short period, which leads to high power operation without enough allowed time for a temperature stabilization of the after-treatment, resulting in high NOx emissions during urban driving conditions. The effect of the power operation on the emissions of NOx is also illustrated in Fig. S2. For instance, higher emissions were measured while driving uphill (km 15–25) than when the same road was driven downhill (km 112–122).

Fig. 3b shows the effect that a low power average in the window has when the MAW approach is used to analyze this set of data. If the power threshold to consider a window as valid is 20% (15%), the amount of windows not considered in analysis is ~80%. Furthermore, in this example, there are not enough windows to calculate results at either 20% (100% of MAW below) or 15% (~80% of MAW below) power threshold. When the boundary is taken out (i.e. no power threshold), the full number of windows can be considered, resulting in 2.39 g/kWh of NOx emitted (see Table 2).

MAW data was also binned by the window average speed as expressed in method 4, with the window average speed was below 50 km/h, this window was categorized as “urban window”, and so on. Table 3 summarizes the MAW emission factors obtained for each operation share. Trip composition may have an effect on the emissions due to different variables that will impact them (e.g., traffic, weather, altitude, idle or low power operation, etc.). As it can be seen, results in the rural speed bin are higher. The average speed of the windows shows a combined operation of urban/motorway operation. On the other hand, no motorway results are shown on Test 4, and this is because the average speed of the MAW on this trip always fell below 75 km/h.

NOx emissions were found to be the highest during the urban operation of each test (ranging from 1.14 to 2.30 g/kWh). The highest emissions ratio between urban and motorway operation was found in Test 1, where NOx emissions in urban operation were ~6 times that of motorway. The EF obtained for Test 4 (2.30 kW/h) was ~2 times compared to the rest of the tests.

3.2. NH3, N2O and PN on-road emissions and measurements

Table 2 summarizes NH3 emission concentrations, PN, NH3 and N2O EFs per window of operation, calculated without boundary conditions
using EMROAD and the MAW methodology during 4 on-road tests (PN only on 3 on-road tests; see Table 2).

The studied vehicle was equipped with sensors that measured NOx concentrations before and after the SCR (see Table S2). The concentrations, measured using the post-SCR NOx sensor were in good agreement with those measured by the Semtech and the QCL-IR systems ($r^2 > 0.9$; see Fig. S3). The SCR system effectively reduced 88% to 97% of the NOx emissions, the excess of this pollutant should then be oxidized to N2 downstream by the AMOX system. The studied vehicle injected 2.0–2.7 kg of urea solution to reduce the NOx emissions during the trips (trips length: 123–155 km), which is approximately 6% of the vehicle’s urea tank for each trip. Although the AMOX system oxidizes the non-reacted NH3, 0.9–2.0 g of NH3 (8–15 mg/kWh integrated over the trip) were still emitted during the trips. NH3, as well as N2O, emissions were observed in correspondence with the signal of urea injection recorded using the ECU, indicating that these emissions are related to the use of the SCR system (see Fig. 4). In the atmosphere this NH3 reacts with nitric acid, formed via oxidation of NOx, to generate ammonium nitrate (NH4NO3), which is a large fraction of PM2.5 mass (Kim et al., 2000; Phan et al., 2013). With SCRs being introduced to the HD fleet at a fast pace, it therefore important to regulate and monitor these emissions.

The obtained average NH3 emission concentrations, calculated applying the MAW approach to all available windows, were lower than the 10 ppm allowed for bench testing (over the WHTC), and ranged from 1.0 to 2.2 ppm (see Table 2). However, they were 1.6 to more than 10 times higher than those reported for a Euro VI engine by Jeon et al. (2016). When expressed as brake-specific emissions, average NH3 emissions varied from 9 to 19 mg/kWh. These emissions are well above the 3.3 mg/kWh reported by Khalek et al. for a series of 2010 engines equipped with SCR and AMOX catalytic converters and tested over the Federal Test Procedure (Khalek et al., 2015). They are also higher than the ~6 mg/kWh reported by Tadano et al. for a Euro V engine tested over the European Steady Cycle (Tadano et al., 2014). However, in a previous study (Suarez-Bertoa et al., 2016) we reported on-road average NH3 emissions from a Euro V HDV (no AMOX system was present in the vehicle) that were up to 7 times higher than those measured from the Euro VI HDV in the present study.

Average N2O EFs were lower than the U.S. N2O emission limit (133 mg/kWh) for engine testing (EPA, 2015), ranging from 50 to 70 mg/kWh. If considered as CO2 equivalents (N2O has 298 times the global warming potential of CO2 over 100 years), the N2O emissions obtained here added ~2% to the CO2 emitted by the vehicle. Average N2O EFs were lower than what reported by Khalek et al. for a series of 2010 engines (93 mg/kWh) (Khalek et al., 2015), but higher than those reported by Tadano et al. (45 mg/kWh) for a Euro V engine equipped with an SCR (Tadano et al., 2014). Average N2O emissions were up to 2.8 times higher than those reported on-road for a Euro V vehicle (Suarez-Bertoa et al., 2016).

Emissions of NH3, N2O and PN were also analyzed on the basis of vehicle operation mode during all tests (Table 3). NH3 and N2O EFs were very similar for the urban, rural and motorway shares of each test, with the exception of Test 4, where the available motorway operation was not enough to complete the equivalent WHTC work required for a window. NH3 EFs ranged from 8 mg/kWh in the motorway share of the Test 3 to 33 mg/kWh of the motorway share of Test 2. N2O EFs ranged from 55 mg/kWh in the urban share of Test 4 up to 85 mg/kWh in the motorway share of Test 2.

The PN emissions can be seen in Table 2. On-road PN emissions resulted on average $4.4 \times 10^{10}$ #/kWh, which is one order of magnitude lower than the current type approval limit ($6 \times 10^{11}$ #/kWh). The results confirm the effectiveness of the vehicle’s DPF. The emissions during the cold start were relatively low, thus the different methods would not have such a strong impact on the emissions as in the case of NOx.

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### Table 3

| NOx [g/kWh] | Test 1 | Test 2 | Test 3 | Test 4 |
|-------------|--------|--------|--------|--------|
| Urban       | 1.15   | 1.60   | 1.14   | 2.30   |
| Rural       | 0.46   | 0.56   | 0.63   | 2.31   |
| MW          | 0.19   | 0.30   | 0.63   | –      |

| NH3 [ppm]   | Test 1 | Test 2 | Test 3 | Test 4 |
|-------------|--------|--------|--------|--------|
| Urban       | 1.8    | 1.9    | 1.1    | 1.0    |
| Rural       | 3.3    | 3.2    | 1.8    | 1.3    |
| MW          | 3.7    | 4.5    | 1.2    | –      |

| NH3 [mg/kWh] | Test 1 | Test 2 | Test 3 | Test 4 |
|--------------|--------|--------|--------|--------|
| Urban        | 21     | 28     | 12     | 11     |
| Rural        | 27     | 27     | 14     | 12     |
| MW           | 28     | 33     | 8      | –      |

| N2O [mg/kWh] | Test 1 | Test 2 | Test 3 | Test 4 |
|--------------|--------|--------|--------|--------|
| Urban        | 72     | 83     | 77     | 55     |
| Rural        | 83     | 84     | 75     | 62     |
| MW           | 80     | 85     | 66     | –      |

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![Fig. 3. (a) Instantaneous NOx emissions vs % of maximum power. (b) MAW based emissions vs MAW average power during Test 4.](image-url)
One topic of concern was the formation of particles downstream of the SCR catalyst (Amanatidis et al., 2014). Fig. 5 shows PN emissions, urea injection and NH$_3$ concentration for Test 4. PN emissions decreased when urea was not injected (time around 5000 s). Although this change was accompanied by a decrease of the speed as well, another part (time around 2000 s) with lower speed had higher emissions when urea was injected (see also Fig. 2b for the speed profile). Higher PN emissions were noticed when urea was injected and there was emission of ammonia, in agreement with Amanatidis et al. (2014).

Overall, the low PN, NH$_3$ and N$_2$O emissions, together with relatively low NO$_x$ emissions, suggest that the vehicle after-treatment system, DOC + DPF + SCR + AMOX, was in good working order.

3.3. GIS analysis discussion

The possibility of using geographical information to assign on-road testing operation category has been the topic of some discussion recently. A comparison between the current share calculation (speed based and duration) of the percentage of urban, rural or motorway share, DOC + DPF + SCR + AMOX, was in good working order.

and a Geographic Information System (GIS) based analyses has been performed in order to highlight the capabilities within each method.

The European Road Map was used to incorporate the motorways network into the urban-rural map of Test 4 area obtained by the reclassification of CLC map. This allowed the comparison between Test 4 land-use based shares of operation (13%, 18% and 69% for the urban, rural and motorway share, respectively) and speed-based shares of operation as they are currently defined by Euro VI legislation (36%, 36% and 28% for the urban, rural and motorway share, respectively) (see Fig. 6).

The CLC inventory does not consider transport network as a land use class, hence only urban and rural shares are present (46% and 54%, respectively for Test 4).

Test 4 map was spatially joined to the urban-rural-motorway map produced. Such geo-processing operation allows merging the attributes from one layer to another, based on the spatial relationship. In other words, it characterizes every point of the Test 4 route with land-use based attribute (i.e. urban, rural or motorway) according to the land use classification of the area crossed. Fig. S4 shows the difference existing in Test 4 urban areas as defined by the speed-based perspective.

![Fig. 4. Instantaneous urea solution injection, NH$_3$ and N$_2$O emission during Test 4.](image)

![Fig. 5. Instantaneous urea injection, PN and NH$_3$ emissions during Test 4.](image)
adopted by the current legislation (red color code on linear trip) in comparison with urban/rural areas defined by land-use perspective (red color code on the underlying land use map).

Furthermore, the Italian Road speed limits map was used for the application of speed-limit-based approach to the boundary definition. The attributes from Italian Road speed limits map were converged to the speed-based approach as currently adopted in Euro VI legislation, land-use perspective without motorways, land-use base perspective with the inclusion of motorways network, road speed-based limits defined by Italian law. Percentages are calculated in distance terms, on the total trip distance of Test 4.

![Comparison of share of rural, urban and motorway operation, under different boundary conditions. From the top: speed-based approach as currently adopted in Euro VI legislation, land-use perspective without motorways, land-use base perspective with the inclusion of motorways network, road speed-based limits defined by Italian law. Percentages are calculated in distance terms, on the total trip distance of Test 4.](image)

Using the GIS approach to categorize the share of operation could result in different operation assignments depending on the criteria adopted while defining them e.g., land use base with or without motorway, speed limit in different countries, among others. Such variations can strongly affect the subsequent data analysis leading to different percentage of share of operation (see Fig. 6) and ultimately different emission factors corresponding to each share. As shown, the application of GIS to define the shares of operation is not trivial and needs much refinement of the criteria definition before it can be considered appropriate for on-road testing. Nonetheless, the use of GIS during on-road testing will be a very useful tool for air quality studies, as it indicates where the pollutants are emitted, clearly discriminating between urban and rural environments.

4. Conclusions

This study, characterising emissions from a Euro VI heavy-duty vehicle, shows the benefits of introducing on-road emissions verification testing into regulation, as well as the achievement of below Euro standards emissions of a compliant vehicle during on-road operation. However, there are areas, both technology- and regulatory-wise, that can be improved.

Our analyses revealed that up to 85% of the NOx emissions measured during the tests performed are excluded if the current boundaries for post-processing of PEMS based data are applied. Thus, as of today, a large fraction of the NOx emitted by the heavy-duty monitored fleet is not reflected by the emission factors calculated. The highest NOx emissions were invariably found on urban operation, which is of great concern for urban air quality and human exposure.

The use of a 20% power threshold as boundary condition resulted in up to 80% of windows being excluded from emissions analysis. Most of these windows pertain to urban operation. Therefore, a lower power threshold should be used or power threshold boundary should be avoided. Moreover, cold start emissions can account for a large fraction of the total NOx emitted, and these are currently also excluded of the analysis.

NH3, PN and N2O emissions, which are still not included within the ISC procedure for on-road emissions measurement, were measured simultaneously for the first time in the present work demonstrating that the instruments are capable of successfully measuring second-by-second data during on-road applications. This study anticipates the applicability of the gaseous emissions post-processing for ISC PEMS based testing applied to PN concentrations. On-road PN emissions range from 2.8 × 10^{10} to 6.5 × 10^{10} #/kWh, which is one order of magnitude lower than the current type approval limit (6 × 10^{11} #/kWh) and confirms the effectiveness of the vehicle’s DPF.

Average NH3 tailpipe concentrations were lower than the 10 ppm allowed for bench testing (over the WHTC). They ranged from 1.0 to 2.2 ppm. Hence, it appears that, for the studied vehicle, NH3 emissions are well controlled by the AMOX. However, the use of this technology has not been implemented in all HDVs. This should be further investigated as it may be critical for N1/N2 category vehicles (vehicles used for carriage of goods, with a maximum mass < 3.5 t and < 12 t, for N1 and N2, respectively, closer in weight to a light-duty vehicle) where SCR systems are not always coupled with AMOX.

N2O emissions were below the US standards (133 mg/kWh), ranging from 50 to 70 mg/kWh. If considered as CO2 equivalents, the N2O emissions added ~2% to the CO2 emitted by the vehicle.

A first attempt to compare land-use and speed based methods for assigning operation mode as they are currently defined by Euro VI legislation was done. Results showed that shares of operation vary significantly, depending on the criteria adopted in their definition. Such variation can strongly affect the data analysis of the on-road data measured during the PEMS test.

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Disclaimer

The opinions expressed in this manuscript are those of the authors and should in no way be considered to represent an official opinion of the European Commission.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.07.168.

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