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JRC TECHNICAL REPORT

Assessment of on-road emissions of refuse collection vehicles

Diesel and Compressed Natural Gas

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In collaboration with:

AMSA: Azienda Milanese Servizi Ambientali

AMSA (acronym for Azienda Milanese Servizi Ambientali) is a company of the A2A group that manages the collection and disposal of municipal waste in the city of Milan and fourteen municipalities in the Milan (surrounding) metropolitan area. AMSA has been managing urban hygiene, waste collection and disposal services in Milan since 1907.

Contents

Abstract

This report summarizes the results of an experimental study assessing the real-world environmental performance and its comparison with laboratory measurements of two Euro VI step C Refuse Collection Heavy-Duty Vehicles. The first is equipped with a common-rail Diesel engine, a Selective Catalytic Reduction, a Diesel Oxidation Catalytic converter and a Diesel Particle Filter and the second is a Compressed Natural Gas vehicle equipped with a Three-way Catalyst.

The objective of this study is to provide support to the future planning and renewal of the Milan waste collection vehicle fleet comparing two different engine technologies (diesel and natural gas fuelled engines) and evaluate the environmental efficiency of engines solutions.

Broadly, the pollutant emissions factors of the tested Diesel vehicle were better than its homologous CNG vehicle (NO_X: 157.1 mg/kWh and 755.3 mg/kWh, PN: $2.23*10^{10}$ #/kWh and $7.19*10^{10}$ #/kWh for the diesel and CNG vehicles respectively). These results are in agreement with the finds of some recent studies [**1**] that indicate that the current notion that natural gas engines are cleaner than diesel might not be valid any longer. However, the JRC would like to stress that this general conclusion is only applicable to the vehicles and the conditions tested in this experimental project and that under no circumstances it can be generalised to other vehicles or fleets.

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Executive Summary

One of the most challenging issues for building sustainable cities is the improvement of municipal solid waste (MSW) management, which requires a substantial effort to reduce its production and improve its collection, transport and treatment systems.

Modern (Euro VI) heavy-duty vehicles have significantly lower emissions compared to older vehicles. However, there are still concerns regarding the emissions of refuse collection vehicles in cities, because they use engines designed for long haulage trucks and consequently not optimised for low speed stop and start driving. The very low average speeds and the frequent stops represent difficult conditions to cope with from the emission reduction perspective. In fact, for short periods, where the exhaust gas temperature is low for the after-treatment devices (cold start, some city conditions), the emissions are relatively high.

In an effort to provide insight on the optimal future planning and renewal of the Milan waste collection vehicle fleet, the Joint Research Centre (JRC) of the European Commission (EC), in collaboration with the Azienda Milanese Servizi Ambientali (AMSA), initiated an on-road emission testing campaign. The aim of this extensive experimental study, performed both under real and laboratory controlled operating conditions was to identify the actual emission levels of the waste collection vehicles, comparing two different engine technologies (diesel and natural gas fuelled engines) and assess the environmental efficiency of the different engines solutions.

For this purpose, we tested a Diesel Euro VI step C and a Compressed Natural Gas (CNG) Euro VI step C refuse collection heavy-duty vehicle both in the laboratory and on the road using a cycle similar to the in-service conformity (ISC) trips for this type of vehicles (N3). The vehicles were also tested using actual refuse collection cycles. The idea was to directly compared the two vehicles' engine technology to evaluate the performance and the pollutant emissions under realistic and controlled operating conditions in order to support a fleet renewal initiative in the city of Milan. Particle and gaseous pollutants were measured using a Portable Emissions Measurement System (PEMS). Additionally, in the laboratory we used laboratory grade gaseous, particle number and FTIR (Fourier-transform infrared spectroscopy) systems to measure the emissions and check the proper operation of the PEMS.

The present work summarizes the results of the aforementioned experimental activity lead on two vehicles (one Diesel and one Compressed Natural Gas), which were tested in three different phases using a portable emission measurement system. The first phase included a similar In-Service Conformity test (ISC_LIKE) and a city simulation cycle (CITY_SIM), the second part involved real world operation in the city of Milan, whilst a third phase was dedicated to the comparison lab test in confined conditions. This report will address mainly the road comparison, while the laboratory tests and the relative comparison together with the real world findings will be object of a future report.

Focusing on CITY_MILAN cycle, which is the most representative of the real in-use conditions, THC calculated emission factors were two orders of magnitude lower in Diesel engine (0.79 mg/kWh) than in CNG (73.49 mg/kWh), even if we have to consider a different limit for CNG engines. Continuing with the analysis of "Urban" routes, CNG truck showed NO_x emission nearly 4 times higher than the Diesel (755.31 mg/kWh vs 157.10 mg/kWh), exceeding the reference limits. The CNG engine PN levels were 3 times higher than in Diesel one. Including also the regeneration events in the Diesel vehicle, the emissions increased the PN significantly, but it still remained below the limit of 6×10^{11} particle/kWh. In the metropolitan cycle (CITY_MILAN) CNG truck has a CO emission reduction of -85 % compared to the Diesel one, with respectively 40.92 and 320.30 mg/kWh. Nevertheless, CO emissions of both tested vehicles appear to be at very low levels, abundantly below the reference limits (4000 mg/kWh). These trends did not vary significantly among the different routes.

In general, Diesel technology presented important advantages with regards to the NO_X, PN, CO_2 emissions as compared to the CNG engine, while the CNG vehicle provided a better CO emission behaviour.

This trade off needs to be carefully analysed prior to decide if a fleet should be shifted towards either technology, mainly because is based only on a limited comparison between the two considered vehicles. Therefore, the conclusions drawn in this report are only valid for the tested vehicles and they cannot be extrapolated or generalised for a larger fleet of vehicles.

1 Introduction

Air pollution has detrimental effects on human health, natural environment, economy and quality of life. It is estimated that more than 400,000 people in the European Union die prematurely due to the consequences of air pollution and another 6.5 million people fall sick because of health implications caused by air pollution annually [**2**]. Improving urban air quality has been the main driver for putting forward several European policies, initiatives, and actions. Road vehicles have historically been one of the main sources of pollutants that affect urban air quality and the main reason for establishing emissions standards of continuously increasing stringency.

In fact, road traffic contributes around 11% to the particulate matter (PM), 28% to black carbon, and 39% to NO_X concentrations in Europe [**3**]. Despite that Heavy-Duty Vehicles (HDVs) represent a small part of the overall vehicle population (<5% of the vehicle population in some major country), a study found that they contributed 40–60% of their road-traffic PM and NO_X emissions [**4**]. In 2016 around 12% of all the air-quality reporting stations in Europe recorded concentrations above the NO_2 limit values; 88% of all concentrations above this limit value were observed at traffic stations [**3**]

Heavy-Duty Vehicles (HDV) constitute a very important vehicle category of the road transport sector, operated in a wide series of activities, from passenger and freight transport to very unique applications. Thus, there is high variability with regard to HDV characteristics, types and possible uses. Their increasing numbers and usage result in significant contribution to gaseous pollutant, particulate matter and greenhouse gas (GHG) emissions, particularly in urban environments, despite the fact that important progress has been made in lowering emissions and fuel consumption from heavy-duty internal combustion engines [**5**, **6**]. This is one of the reasons why HDV emissions regulations are becoming more and more stringent worldwide. Following this trend, Europe introduced the Euro VI standard which includes more stringent emission limits for hydrocarbons, PM and NO_X, while for the first time a limit for solid PN emissions was set.

The pollution from engines and vehicles is controlled by type approval tests where emission standards have to be fulfilled (for example in the European Union (EU) the "Euro" standards). Regarding heavy-duty vehicles, the type approval of an engine is conducted in a test dynamometer following a prescribed test cycle where the engine revolutions and torque are varied. This engine then can be used for various applications for instance in a truck (category N3) or a bus (category M3). Euro VI legislation [**7**] 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 that the emissions of the engine are below the regulated limits throughout the engine's useful life without having to extract the engine from the vehicle. 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 shares of operation and route composition, amount of work performed by the engine, etc.). For N3 vehicles (trucks) the cycle consists of 20% urban (speed ≤50 km/h), 25% rural (speed between 50 and 75 km/h) and 55% motorway (speed >75 km/h) phases in this order, while for comparable M3 urban buses (class I, II or Class A) the shares are 70% urban and 30% rural.

An amendment to this regulation [**8**], called step D, which entered into force from September 2018 for new types (September 2019 for all new vehicles) changed the time shares to 25% (urban), 30% (rural) and 45% (motorway) [**9**]. Another amendment (step E) in the future is planned to include particle number testing and cold start in the evaluation. Thus, for the same trip and vehicle, the final emissions results can be different depending on the regulatory step and the evaluation method [**10**].

Refuse collection vehicles are at one extreme of the operating condition range for heavy-duty engines. Refuse trucks have unique operating characteristics because they have to start and stop frequently in between disposal bins. This results in numerous accelerations, decelerations, and idling for short intervals. The refuse trucks also have to travel on the highway (motorway) to and from the fleet facilities, the service area, and, dump site, which involves high speed cruising. For the ISC test, Euro VI engines of refuse collection vehicles are assessed over a trip that is meant for long haulage trucks (N3). This is because refuse collection vehicles are produced as regular trucks on which the special bodywork and auxiliaries are added later, often by a different manufacturer. This mismatch between regulation and real operation resulted in high emissions of this category of vehicles for older [**5**, **11**-**15**] but even recent technology vehicles [**12**,**15**-**17**]. This raised concerns about their sustainability for city applications.

At the moment, during PEMS on-road testing for type-approval and ISC testing only NO_X, CO, and total hydrocarbons (HC) are measured. Particle number (PN) will be introduced with step E, nevertheless during this campaign also solid particle were measured.

One of the main objectives of this study is to measure the emissions of a heavy-duty refuse collection vehicle equipped with different engine technology (Diesel and Compressed Natural Gas) under real operation conditions and compare them with the ISC_LIKE tests for this vehicle category.

In order to assess the uncertainty of the measurements, the PEMS was compared with laboratory grade analyses on a chassis dynamometer. Additionally, the same on-road cycles were retested in the laboratory in order to investigate possible discrepancies between real world emissions and laboratory testing.

2 Emission Factors of Euro VI heavy-duty refuse collection vehicle

2.1 Scope

The Refuse Collection PEMS campaign was launched under the patronage of AMSA S.p.A. to compare the actual state of the art in Euro VI Diesel and Compressed Natural Gas (CNG) refuse collection vehicles on real working condition.

2.2 Objectives

This Programme is dedicated to provide insight on the optimal future planning and renewal of the Milan waste collection vehicle fleet giving advices on the progress of Euro VI and on the comparison between Diesel and CNG vehicles.

The objectives of the program were defined as follows:

- Evaluate the particle and gaseous pollutants emissions using PEMS under city operation on a real refuse collection cycle (in mg/kWh or mg/km);
- Compare the PEMS with laboratory grade equipment;
- Compare laboratory and on-road tests;
- To investigate the emission factors of unregulated pollutant as NH_3 and N_2O in laboratory.

3 Tests description

In this study two different Euro VI waste collection trucks were investigated regarding their emissions: the first one representing a Euro VI Diesel Engine conventional trucks and the second one, a Euro VI fuelled with compressed natural gas (CNG). The tests were performed during normal work shifts in the city of Milan (Italy) and on a track following a specific driving pattern (see paragraph 3.4 for further details). The vehicles had been equipped with portable emission measurement systems (PEMS) and the emission was monitored and recorded second-by-second. The methodology and the results are presented in the next chapters.

3.1 Tested vehicles

Both vehicles (see **Figure 1** and **2**) were provided by the Environmental services company of Milan (AMSA, Azienda Milanese Servizi Ambientali). The refuse collection vehicles were equipped with a rear container loader that can lift small containers. The waste is compressed against a moving wall, powered by the same engine that moves the vehicle. The main characteristics of the engines and the vehicles can be found in **Table 1** and in **Figure 3.**

Figure 1. AMSA tested vehicle during service (1)

Source: AMSA, 2018

Figure 2. AMSA tested vehicle during service (2)

Source: AMSA, 2019

Table 1. Engines and Vehicles characteristics

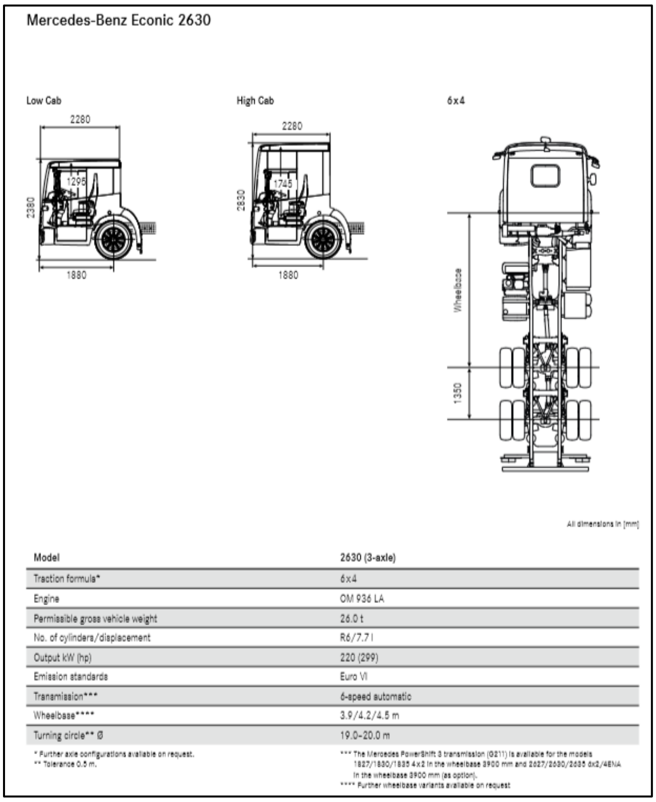
Technical data	DIESEL	CNG
Vehicle model	Mercedes-Benz NGE-L62N Farid T23C	Mercedes-Benz NGE-L62N Econic
Engine model	Daimler AG OM936 LA	Daimler AG M936 G
Engine type	Compression Ignition with turbocharger and EGR	Single-stage turbocharged and EGR
Fuel injection system	Common rail	Spark plugs pencil-type ignition coils
Vehicle mass empty / max (kg)	15500 / 26000	15500 / 26000
Displacement (cm^3)	7698	7698
Cylinders	6 in-line	6 in-line
Rated Speed	1350 rpm	1500 rpm
Engine max power	220 kW at 2200 rpm	222 kW at 2200 rpm
Engine max torque	1200 Nm at 1200-1600 rpm	1200 Nm at 1200-1600 rpm
After-treatment	DOC+DPF+SCR	TWC
Axle configuration	6x2/4 ENA	6x2/4 ENA
Transmissions	6-speed automatic transmission	6-speed automatic transmission
Permissible gross vehicle weight	26,0 t	26,0 t
Production year	6/2018	6/2018
Mileage	3200	Brand new
Emission standard	Euro VI step C	Euro VI step C

EGR=Exhaust gas recirculation; DOC=diesel oxidation catalyst; DPF=Diesel Particulate filter; SCR=Selective catalytic reduction

Source: AMSA, 2018

Figure 3. Vehicle outline and main characteristics (a: Diesel vehicle; b: CNG vehicle)

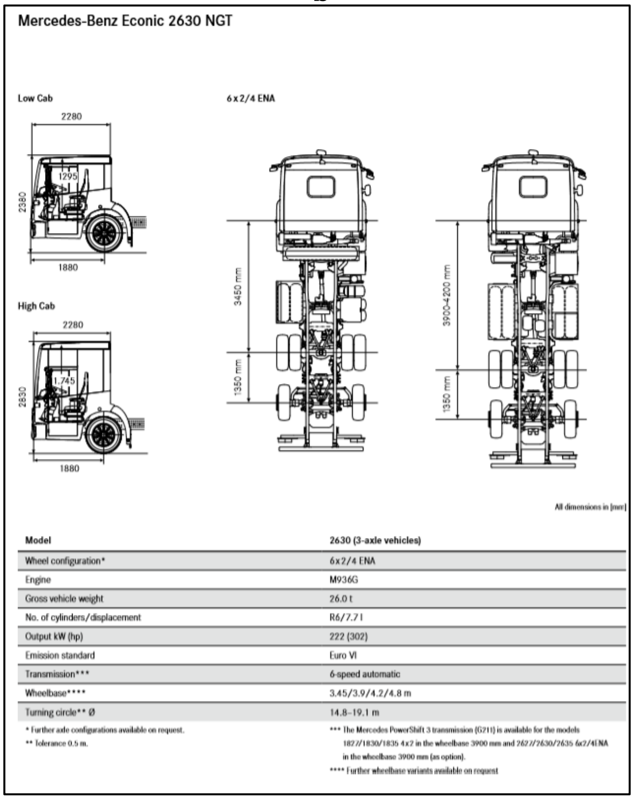
a



Model	2630 (3-axle)
Traction formula*	6x4
Engine	OM 936 LA
Permissible gross vehicle weight	26.0 t
No. of cylinders/displacement	R6/7.7 l
Output kW (hp)	220 (299)
Emission standards	Euro VI
Transmission***	6-speed automatic
Wheelbase****	3.9/4.2/4.5 m
Turning circle** Ø	19.0–20.0 m

* Further axle configurations available on request.
** Tolerance 0.5 m.
*** The Mercedes PowerShift 3 transmission (G211) is available for the models 1827/1830/1835 4x2 in the wheelbase 3900 mm and 2627/2630/2635 6x2/4ENA in the wheelbase 3900 mm (as option).
**** Further wheelbase variants available on request

b



Model	2630 (3-axle vehicles)
Wheel configuration*	6x2/4 ENA
Engine	M936G
Gross vehicle weight	26.0 t
No. of cylinders/displacement	R6/7.7 l
Output kW (hp)	222 (302)
Emission standard	Euro VI
Transmission***	6-speed automatic
Wheelbase****	3.45/3.9/4.2/4.8 m
Turning circle** Ø	14.8–19.1 m

* Further axle configurations available on request.
** Tolerance 0.5 m.
*** The Mercedes PowerShift 3 transmission (G211) is available for the models 1827/1830/1835 4x2 in the wheelbase 3900 mm and 2627/2630/2635 6x2/4ENA in the wheelbase 3900 mm (as option).
**** Further wheelbase variants available on request

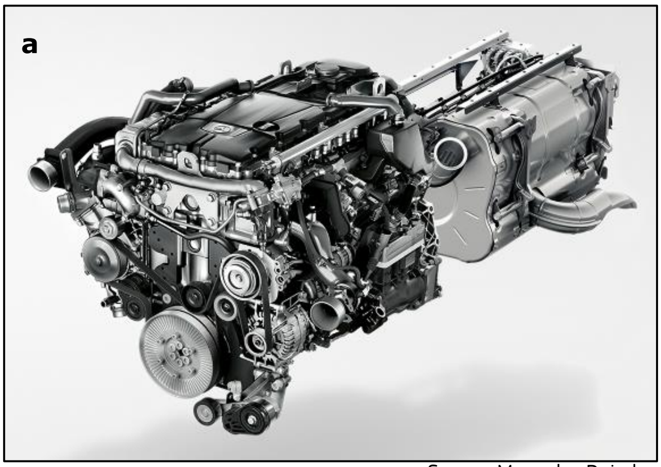
Source: Mercedes Daimler website, 2019

3.1.1 Engine characteristics

The Diesel (**Figure 4a**) and CNG (**Figure 4b**) engines have the same nominal performances. The modern 6-cylinder engine fitted to the Econic provides an output of 220 kW (299 HP) at 2200 rpm and a maximum torque of 1200 Nm in the nominal engine speed range between 1200 and 1600 rpm (see reference performances: Power and Torque curve in **Figure 5**).

Figure 4. Engine outlook. **a**: Daimler AG OM936 LA (Diesel); **b**: Daimler AG M936 G (CNG)

a

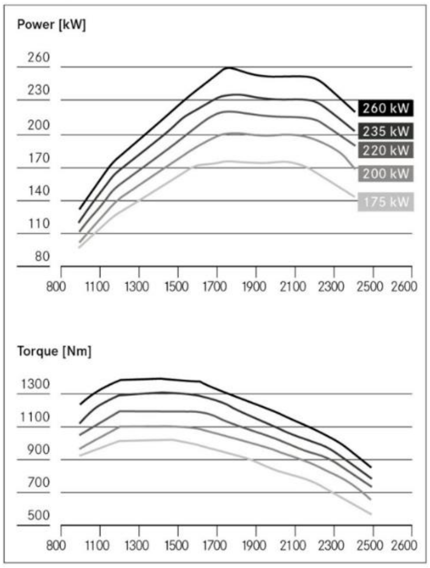


b

Source: Mercedes Daimler website, 2019

Figure 5. Daimler M936 engine power and torque curve (in the red circle the values valid for both Diesel and CNG engines)

Performance



Rated power and maximal torque

Rated power	[kW/hp]	175/238	200/272	220/299	235/320	260/354
at engine speed	[rpm]	1800	1800	1800	1800	1800
Maximal torque	[Nm]	1000	1100	1200	1300	1400
at engine speed	[rpm]	1200-1600	1200-1600	1200-1600	1200-1600	1200-1600

Source: Mercedes Daimler website, 2019

3.2 In-use fuels

DIESEL ENGINES:

Diesel B7 market fuel (EN590) was used (biofuel content 6.2% FAME, sulphur content 8.4 ppm, polycyclic aromatics 3.4%). A commercial grade liquid reductant was used for the Selective Catalytic Reduction (SCR) system (Bluechim® from Chimitex, Italy).

COMPRESSED NATURAL GAS (CNG) ENGINES:

Natural Gas is a gaseous fossil fuel, consisting mainly of methane, with volume ranging from 90 to 98%. The remaining constituents include in particular ethane, propane, butane and nitrogen. Natural gas used typically in a compressed form characterises with low energy density. Due to a much lower density of gas fuels and in consequence lower energy per volume unit the vehicle must be specially adapted to gas fuelling. Effective use of energy contained in gas fuel necessitates changes in the power unit [**18, 19**].

Table 2 depicts a comparison between Diesel fuel and CNG based on chemical and physical properties.

Table 2. Fuels comparison based on chemical and physical properties

PROPERTY	FUELS	
	Low Sulphur Diesel	Compressed Natural Gas (CNG)
Chemical Structure	C_8 to C_{25}	CH_4 (majority), C_2H_6 and inert gases
Fuel Material (feedstocks)	Crude Oil	Underground reserves and renewable biogas
Energy Content (lower heating value)	11.83 kWh/kg	13.1 kWh/kg
Energy Content (higher heating value)	12.67 kWh/kg	14.5 kWh/kg
Physical State	Liquid	Compressed Gas
Cetane Number	40-55	N/A
Pump Octane Number	N/A	120+
Density @ 0°C	0.846 kg/l	0.777 kg/m3
Flash Point	74 °C	-185 °C
Autoignition Temperature	~315 °C	-17 °C
Maintenance Issues		High-pressure tanks require periodic inspection and certification.
Energy Security Impacts	Manufactured using oil, of which nearly 1/2 is imported	CNG is domestically produced from natural gas and renewable biogas.

Source: afdc.energy.gov, 2019

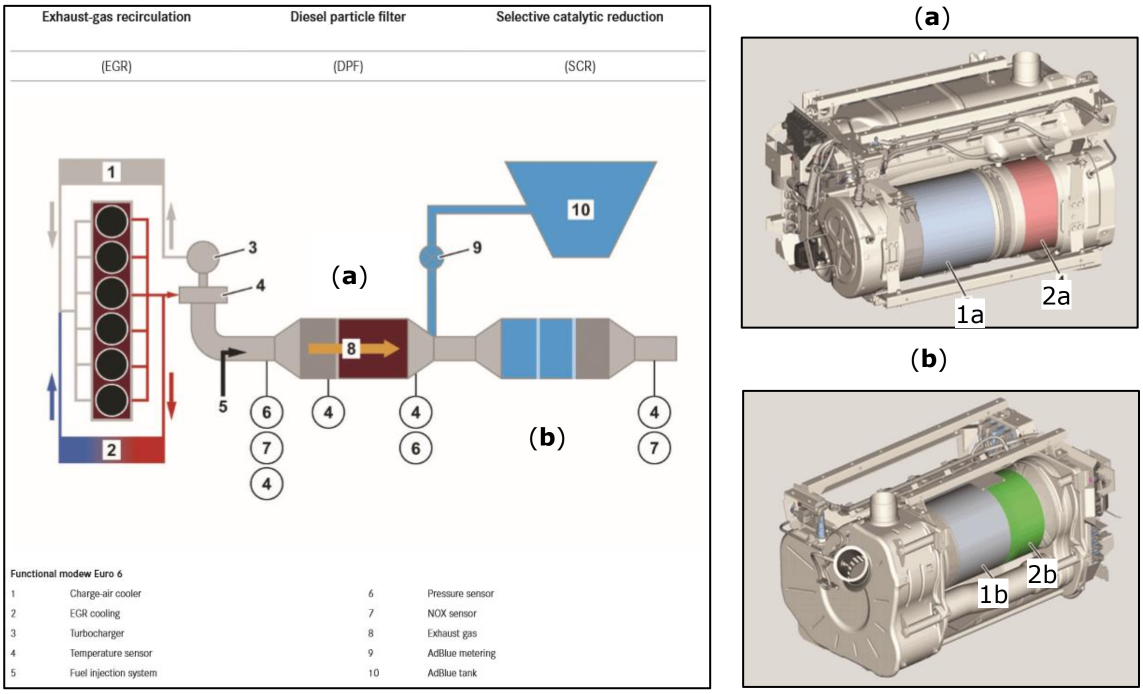
3.3 After-treatment devices

3.3.1 Diesel vehicle

For conventional Euro VI Diesel engines, to fulfil the standards of exhaust emission, a SCR (Selective Catalytic Reduction is required. SCR acts by converting hazardous substances in exhaust gases from engines, in particular nitrogen oxides and their transformation into vapour and neutral nitrogen. The transformation is accomplished in the presence of non-toxic aqueous urea solution (AdBlue®) as catalyst of exhaust gases. The electronic systems of engine management doses AdBlue® in a separate tank and thereafter under high pressure is injected using a metering valve directly to the reactor, where the AdBlue® reacts with exhaust gas and decomposes into nitrogen and water vapour (See **Figure 6** for reference). In addition to SCR system, also a DOC (Diesel Oxidation Catalytic) converter and DPF (Diesel Particle Filter) are needed in order to meet the requirements of the Euro VI legislation and the customer request for minimal consumption.

First, the exhaust emissions flow through the oxidation catalytic converter. This converts the existing hydrocarbons and carbon monoxide to carbon dioxide and water. Furthermore, some of the nitric oxide (NO) is oxidized to nitrogen dioxide (NO_2). The particles are isolated and collected in the porous filter structure of the DPF through the process of adhesion. In the downstream particle filter, the NO_2 reacts with the deposited soot to become NO and CO_2. The deposits are broken down – the system regenerates: "passive regeneration". In order to achieve a complete filter regeneration, the "passive regeneration" is coupled with an "active regeneration". With the active regeneration, a reaction takes place between O_2 and soot at temperatures above the passive scope of regeneration. In order to reach the temperatures required here, the exhaust gas temperatures are increased by injecting HC in the form of diesel fuel. The HC reacts exothermally to the oxidation catalyst and facilitates the increase in temperature of the exhaust gas. Then the exhaust gas flow enters into the SCR converter undergoing the reaction described above.

Figure 6. Exhaust after treatment devices – Diesel vehicle **a**: DOC(1a)+DPF(1b); **b**: SCR(1b)+ASC(2b).



Source: AMSA, 2018

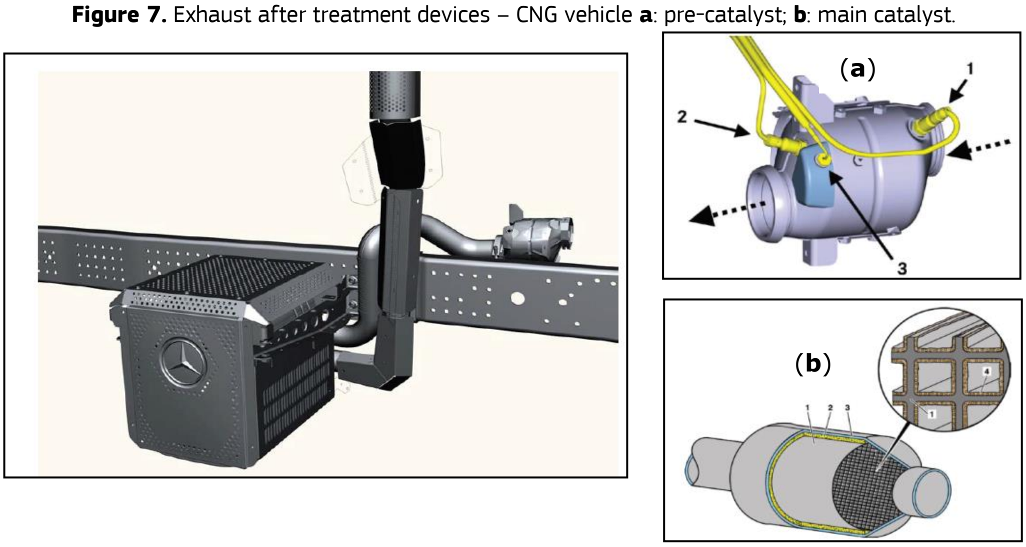
3.3.2 CNG vehicle

The CNG exhaust gas system (see **Figure 7**) consists of a pre-catalyst (**a**) and a main catalyst (**b**) both in the 3-way version. The pre-catalyst is flanged directly on the turbocharger. Thanks to its position near the engine, it quickly reaches operating temperature. The catalytic reaction of the flow of exhaust gases takes place mostly inside it, despite its small size. Behind the pre-catalyst there is a lambda probe for monitoring oxygen content of the exhaust gases

The ceramic monoliths are ceramic bodies which contains thousands of small channels. The exhaust gas passes through them. The ceramic is composed of magnesium silicate and aluminium resistant to high temperatures. The monolith, which is extremely sensitive to tensions, is integrated in an elastic wire mesh made of high-alloy steel wires and is fixed in a double-walled stainless-steel casing. The ceramic monoliths require an aluminium oxide substrate (Al_2O_3), which increases the effective surface of the catalyst by about 7000 times. In three-way catalysts, the effective catalytic layer, in noble metal, applied on the substrate is composed of platinum, rhodium and palladium. Platinum and palladium accelerate the oxidation of hydrocarbons (HC) and carbon monoxide (CO).

Rhodium helps in the reduction of nitrogen oxides (NO_X).

Figure 7. Exhaust after treatment devices – CNG vehicle **a**: pre-catalyst; **b**: main catalyst.



Source: AMSA, 2018

3.4 Test trips and cycles

The experimental work was divided into three phases. During phase 1 (phase 1a), two waste collection trucks, one equipped with a Euro VI diesel engine and the second equipped with a Euro VI CNG engine, were instrumented with Portable Emission Measurement Systems (PEMS) and their exhaust emissions were measured on a road test “similar” to an In-Service Conformity test (called ISC_LIKE). A compliant ISC test (ISC_COMPLIANT) will be also presented at the end of this discussion. In addition (phase 1b), a city simulation cycle (CITY-SIM) was performed internally in the JRC Ispra-site, following a driving/operating cycle simulating the typical conditions observed during previous testing campaign. The word “similar” stands for that the cycle has all the characteristics of a compliance In-Service Conformity Cycle, even if, in some cases, the time sharing between the different segment in terms of speed profile is not fully respected.

In phase 2, the same two refuse collection trucks, were equipped with the same PEMS equipment and tested during normal work conditions in the city of Milan.

Then a third part of laboratory analyses has been introduced. They will not be presented in this report, except for the validation of PEMS instruments and the assessment of Ammonia and Nitrous oxides.

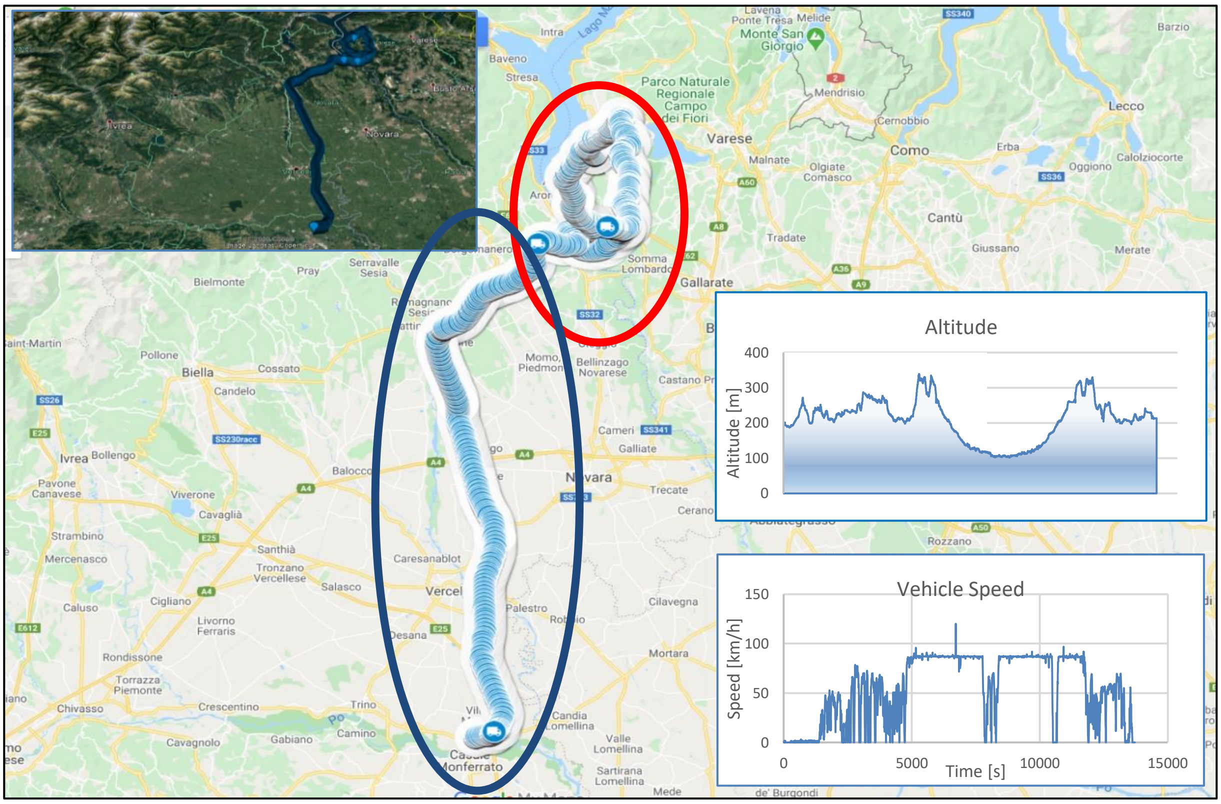
More in detail, the test cycles used for the evaluation of the vehicles were deeply investigated in the next paragraphs. **Figures 8**,**9** and **10** give a complete overview of the tracks as well as of their altitude and vehicle speed profiles.

3.4.1 “Similar” In-Service Conformity test (ISC_LIKE)

ISC_LIKE road track is an extended version of the cycle required by the regulation ($ISC_{official}$) for the specific engine category (N3) to assess the emissions of the vehicle in service. It consists of an urban part (U) with cold start (U-cold), rural part (R), and motorway part (M). For Diesel vehicles, in some trips, there was a regeneration at the last part of the motorway phase (M-Reg). The Urban (U) and the Rural (R) part are included in the area limited by the red circle. Instead the Motorway (M) session is included in the area highlighted in the blue circle. See **Figure 8** for reference.

Figure 8. ISC_LIKE test cycle.

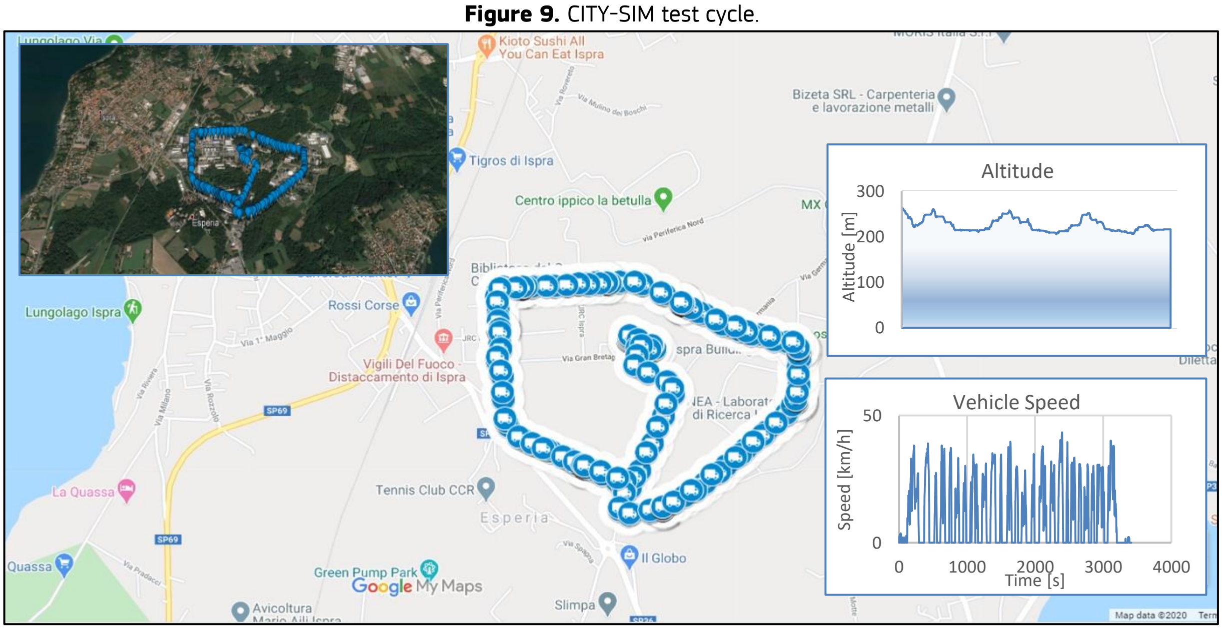
JRC, 2018; Google Earth, 2019



3.4.2 City simulation (CITY_SIM)

It is a custom-made cycle which simulates the operation of the vehicle in the city with start and stops and compaction activities (but with no waste, so the hydraulic pumps of the vehicle were activated to run an entire cycle, but without compressing any material/garbage). It starts with hot engine (coolant temperature around 70°C). This track cycle has been designed completely inside the JRC Ispra-site perimeter (**Figure 9**).

Figure 9. CITY-SIM test cycle.

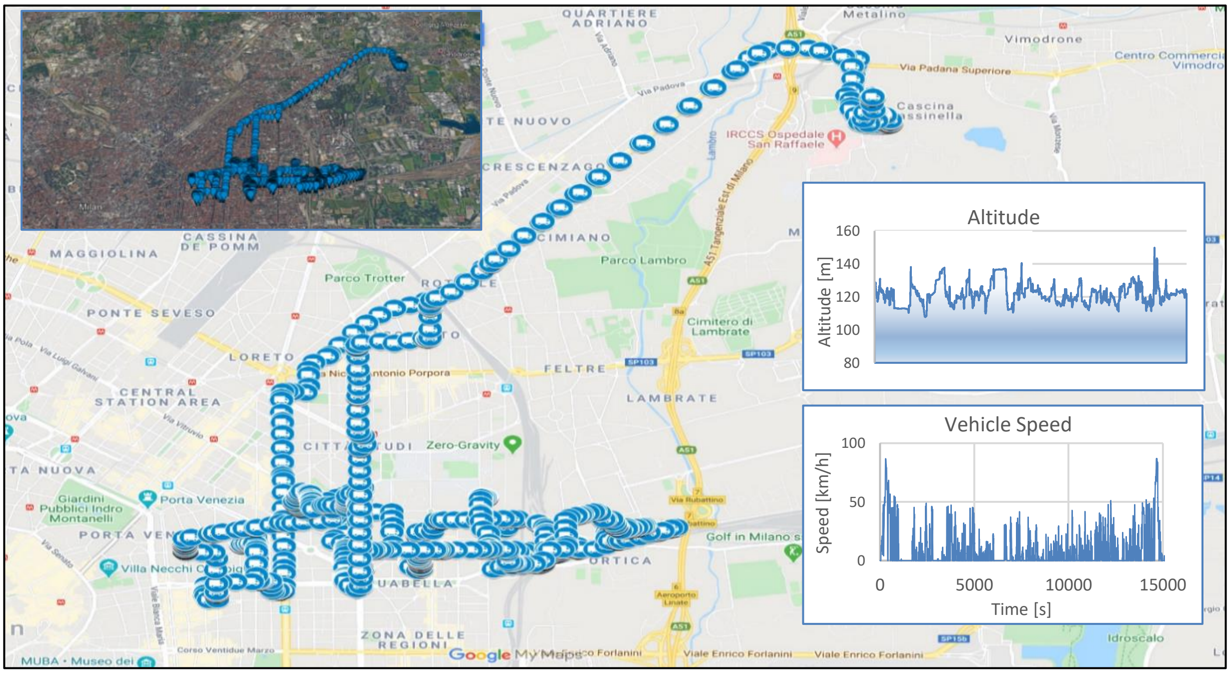


JRC, 2018; Google Earth, 2019

3.4.3 Milan refuse collection cycle (CITY_MILAN)

This is the real urban cycle. **Figure 10** depicts an actual refuse collection cycle used in the city of Milan. Tests were performed during normal work shifts on a track following a specific driving pattern.

Figure 10. CITY test cycle.



JRC, 2018; Google Earth, 2019

It consists of a part from the depot to the city (Approach), the refuse collection (Collection) with actual trash pickup and compaction, and the return to the dump and depot (Return). It starts with cold engine. The cold start phase in CITY_MILAN lasted on average 600-700 seconds and it was completely included in the approach parts (with an average duration of 900/950 seconds). In some cases, the emission factors regarding this part could be very close to the cold start phase). Obviously, in this cycle the compaction activities are real because the hydraulic pumps pressed the refuse materials collected during the cycle.

3.4.4 Additional important cycles features

The ISC_LIKE cycle and the CITY_SIM cycles were tested also in the heavy-duty chassis dynamometer laboratory, but they will not be reported in the present document. The most important statistics of the cycles are summarized in **Table 3** and in **Table 4**. For both vehicles, the mean speeds ranged from around 6 (CITY – Collection) to 88 km/h (ISC_LIKE – Motorway). The idling time was maximum in the CITY test cycle (around 60%), while is less in ISM_LIKE and in CITY_SIM, respectively around 5% and 40%. The mean power of the cycles ranged from 13% (CITY - Collection) to 38% (ISC_LIKE -Motorway) for the Diesel truck and it ranged from 10.6% (CITY - Collection) to 50.8% (ISC_LIKE -Motorway) for the CNG truck. The work to distance ratio (W/D) ranged from 1.01 (Diesel) and 2.34 (CNG) in the ISC_LIKE MOTORWAY part to 5.10 (Diesel) and 3.9 (CNG) in the COLLECTION part of the CITY cycle. The cold start was approximately 4-5% of the total trips time. In the Diesel Vehicle, the mean SCR temperature was above 200°C in all cases, except at the cold start parts (U-cold and Approach). The CNG vehicle presented average exhaust temperature, measured at the probe located in the EFM, higher than the Diesel vehicle. The difference is, on average, of around 110°C. The minimum average temperature was registered in the CITY pattern during the APPROACH phase (Diesel 383,9°C vs CNG 495.5°C), and a maximum in the ISC_LIKE during MOTORWAY part (Diesel 514.3°C vs CNG 636.7°C). The exhaust temperature during the REGENERATION phase in the Diesel truck (659.9°C) has not been considered in the comparison. These data may slightly differ from the percentages stated in previous studies [**20**] due to the different methodology used.

Table 3. Speed classification for the 3 different test patterns (ISC_LIKE, CITY-SIM, CITY). For every sub speed category (U-R-M), the time sharing in percentage and average speed are reported divided by vehicles (Diesel or CNG).

		ISC_LIKE				CITY_SIM				CITY _MILAN			
Speed Classification	**Range**	Time Share [%]		Average Speed [km/h]		Time Share [%]		Average Speed [km/h]		Time Share [%]		Average Speed [km/h]	
		Diesel	**CNG**	**Diesel**	**CNG**	**Diesel**	**CNG**	**Diesel**	**CNG**	**Diesel**	**CNG**	**Diesel**	**CNG**
Urban [U]	< 50 km/h	38.0	36.5	32.1	28.9	100	100	13.3	13.3	98.3	97.1	6.9	6.6
Rural [R]	50-70 km/h	19.3	21.4	65.2	64.1	-	-	-	-	0.9	1.3	64.6	63.5
Motorway [M]	>70 km/h	42.7	42.0	88.3	88.4	-	-	-	-	0.8	0.7	85.8	83.6

Source: JRC, 2019

From **Table 3** and **4,** it is clear that in all the different test patterns, the main statistics (distance, average speed, time sharing) have roughly the same values between the Diesel and the CNG vehicle. This means that it is possible to compare the two vehicles on the same basis. Regarding the CITY_MILAN test performed in Milan and the CITY_SIM performed inside the JRC, in **Table 3** the speed classification maintains the same bins of the ISC as foreseen by the Regulation(EU)582/2011 [**7**] and subsequent Regulation(EU)1718/2016 [**8**], even if during the emission analysis in this study, the CITY_SIM will be treated as a unique bin, while the CITY will be divided in three phases: APPROACH, COLLECTION and RETURN as described in section **3.4.3**. In the “Results and analysis of studies” chapter (**Chapter 5**) also a so called ISC_COMPLAINT test pattern will be reported. The statistics will be introduced in the above mentioned session. The ISC_COMPLIANT test is an In-Service Conformity test which starts from the ISC_LIKE data set, in which the final part has been cut to better fit to the time sharing as prescribed by the Regulation(EU)582/2011 [**7**]. The two approaches do not give high variations on the final emission results (see **Paragraph 5.3** for further details) .

Table 4. Statistics of the test cycles (W/D is the ratio between Work and Distance; Texh is the exhaust temperature measured at the Exhaust Flow Meter probe). M-REG refers to the regeneration events that is applicable only at the Diesel vehicle. The regeneration always was happened in the motorway phase.

		ISC_LIKE													
	Unit	COMPLETE		U		R		M		U-COLD		IDLE		M-REG	
		Diesel	CNG	Diesel	CNG	Diesel	CNG	Diesel	CNG	Diesel	CNG	Diesel	CNG	Diesel	CNG
Duration	s	12395.5	12562.3	4707.0	4591.5	2391.0	2689.3	5297.5	5281.5	1176.0	706.5	351.5	682.8	1800.0	-
Duration fraction	%	100.0%	100.0%	38.0%	36.5%	19.3%	21.4%	42.7%	42.0%	9.5%	5.6%	2.8%	5.4%	17.5%	-
Distance	km	215.3	214.6	42.0	37.1	43.3	47.9	130.0	130.2	9.3	4.6	0.0	0.0	39.8	-
Distance fraction	%	100.0%	100.0%	19.5%	17.3%	20.1%	22.3%	60.4%	60.7%	4.3%	2.1%	0.0%	0.0%	21.0%	-
Mean speed	km/h	62.5	61.5	32.1	28.9	65.2	64.1	88.3	88.4	28.2	23.1	0.0	0.0	79.6	-
Work	kWh	219.5	279.8	46.6	59.8	40.5	50.8	632.3	169.1	13.4	10.7	0.4	2.1	43.0	-
Mean / Max Power	%	29.0%	35.2%	16.2%	21.3%	27.8%	31.0%	40.9%	52.4%	18.6%	24.1%	1.9%	5.1%	38.0%	-
W/D	kWh/km	1.02	1.30	1.11	1.61	0.94	1.06	4.86	1.30	1.45	2.34			1.08	-
Mean Texh (EFM)	K	447.9	595.1	426.7	548.2	453.4	585.4	514.3	636.7	398.3	435.0	405.1	506.7	659.9	-

Source: JRC, 2019

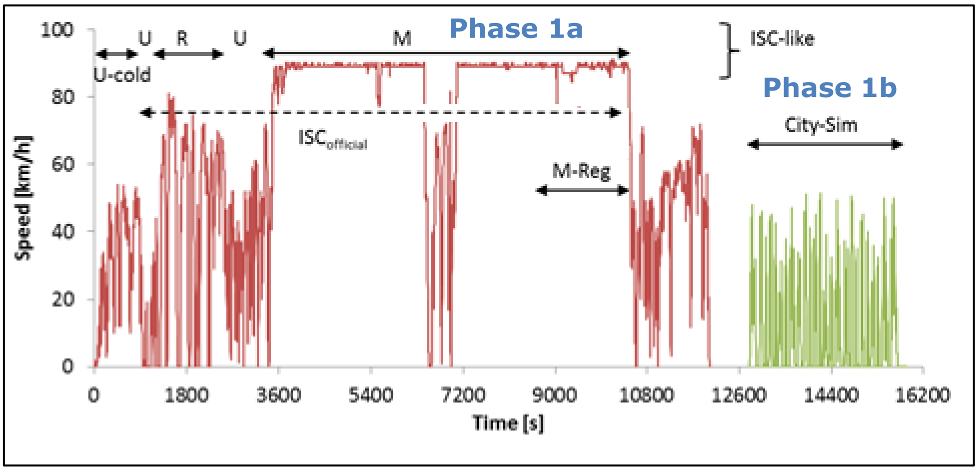
		CITY_SIM						CITY_MILAN									
	Unit	COMPLETE		U		IDLE		COMPLETE		IDLE		Approach		Collection		Return	
		Diesel	CNG	Diesel	CNG	Diesel	CNG	Diesel	CNG	Diesel	CNG	Diesel	CNG	Diesel	CNG	Diesel	CNG
Duration	s	3053.0	3019.0	3053.0	3013.5	1260.0	1307.5	16000.0	15747.0	9138.5	8795.0	900.0	944.0	13100.0	12825.0	2000.0	2054.0
Duration fraction	%	100.0%	100.0%	100.0%	99.8%	41.3%	43.3%	100.0%	100.0%	61.4%	60.5%	5.6%	6.0%	81.9%	81.4%	12.5%	13.0%
Distance	km	11.2	11.2	11.2	11.1	0.0	0.0	37.8	35.7	0.0	0.0	7.6	7.8	21.2	21.5	9.0	6.4
Distance fraction	%	100.0%	100.2%	100.0%	99.4%	0.0%	0.0%	100.0%	100.0%	0.0%	0.0%	20.1%	22.0%	56.1%	60.2%	23.8%	17.8%
Mean speed	km/h	13.3	13.4	13.3	13.3	0.0	0.0	8.0	7.9	0.0	0.0	30.4	29.9	5.8	6.0	16.2	17.4
Work	kWh	25.0	35.5	25.0	35.5	5.1	5.2	130.6	110.0	43.9	34.6	13.6	16.4	108.1	83.2	19.5	10.3
Mean / Max Power	%	13.5%	19.3%	13.5%	19.3%	6.7%	6.5%	14.4%	11.9%	8%	6.5%	25.0%	28.5%	13.0%	10.6%	16.0%	12.8%
W/D	kWh/km	2.2	3.2	2.2	3.2			3.5	3.1			1.8	2.1	5.1	3.9	2.2	1.6

Mean Texh	K	428.9	543.3	428.9	543.2	423.5	531.0	437.7	554.2	455.3	545.2	383.9	495.8	459.5	557.3	468.4	566.0

Source: JRC, 2019

Figure 11 shows also the ISC_COMPLAINT (called "ISC official" in the figure) speed profile.

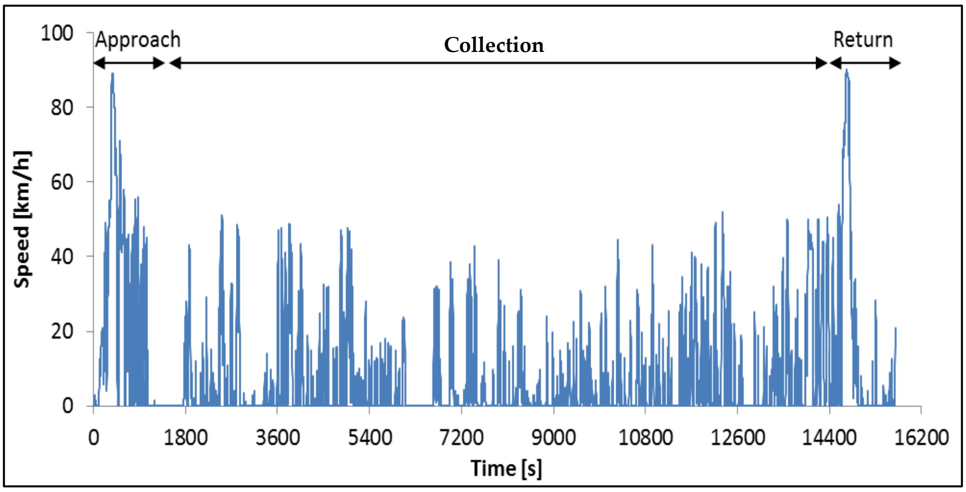
Figure 11. Detailed vehicle speed profile used during Phase 1 (ISC_LIKE and CITY_SIM). **a**: ISC_LIKE: In-Service Conformity with engine cold start consisting of Urban (U), Rural (R) and Motorway (M) parts. Testing the Diesel vehicle, in some cases, there was regeneration in the last part of the motorway section (M-Reg);
b: CITY_SIM: The simulated refuse collection cycle with engine in hot start conditions



Source: JRC, 2019 [**20**]

CITY_MILAN routes (**Figure 12**) represented the real operations during the actual refuse collection cycle, consisting of the approach to the city (APPROACH), the refuse collection (COLLECTION) and the return to the depot (RETURN) parts. Obviously in this phase the compaction activities were real because the hydraulic pumps pressed the refuse materials collected during the cycle.

Figure 12. Detailed vehicle speed profile used during phase 2 (CITY_MILAN).



Source: JRC, 2019 [**20**]

3.5 Test executions

3.5.1 Test Equipment

Exhaust emissions were measured by means of a portable emission measurement system (PEMS). The system consists of a set of analyzers and an exhaust flow meter used to measure the exhaust mass flow.

The PEMS had to comply with the following general requirements:

1. To be small, lightweight and easy to install;
2. To work with a low power consumption so that tests of at least 4.5 hours can be run with few set of batteries;
3. To measure and record the concentrations of NO_X, CO, CO2, THC gases in the engine exhaust;
4. To measure and record the concentrations of solid PN (Particle Number) in the engine exhaust;
5. To record the relevant parameters (engine data from the ECU, machine position from the GPS, weather data, etc.) on an included data logger.

The EFM systems used to test the machinery had to comply with the following general requirements:

1. To be small, lightweight and easy to install;
2. The pipe size and diameter should be chosen according to the truck exhaust flow values (see EFM manufacturer recommendation);
3. To measure and record the Exhaust Mass Emission in appropriate units (e.g. kg/h).

For both laboratory and on-road tests a Semtech-DS PEMS supplied by Sensors Inc. (Michigan, US [**21**]) was used to measure gaseous pollutants. It sampled via a heated line at 191°C downstream of a 4 inches exhaust mass flowmeter (EFM) connected to the tailpipe of the vehicle. The EFM is a pitot tube, based on the Bernoulli principle, equipped with differential pressure devices and thermocouples which measure the exhaust temperature. This technique, also known as “averaging Pitot”, was proven to be reliable over time and quite accurate during the large amount of testing hours. The EFM accuracy over a typical test cycle is better than ±3.0%, with a resolution of 0.003m^3/min. PEMS measured hydrocarbons (HC) in a FID (Flame ionization detector), NO_X ($NO+NO_2$) in a NDUV (non-dispersive ultraviolet), and CO and CO_2 in a NDIR (non-dispersive Infrared) analyser respectively. The technical characteristics of the instrument are presented in **Table 5**. The PEMS included a weather station, enabling the measurement of the temperature, pressure and humidity of the ambient air, and a GPS (Global Positioning System) for the determination of the vehicle speed and altitude. The required power was supplied by external batteries. Before each test the PEMS was zeroed and calibrated with span gases. Note that the Semtech-DS has been replaced in the manufacturer’s catalogue by Semtech-DS+ (2014 some parts, 2018 the complete unit), but nevertheless the older model is widely used [**22**,**23**].

For particle emissions a modified Nanoparticle Emission Tester (NPET, from HORIBA, Kyoto, Japan) [**24**] was used both in the laboratory and on the road. The first diluter (10:1) was located directly at the sample probe at the tailpipe. Using a 4 meters line the diluted aerosol was brought to the main cabinet where a heated catalytic stripper at 350°C removed the volatile and semi-volatile particles. A second dilution (10:1) cooled down the aerosol and brought the concentration to the measuring range of the isopropyl alcohol-based CPC (TSI, Shoreview, MN, USA) model 3007 with 50% counting efficiency at 23 nm (with modified saturator and condenser temperatures).

A connection to the Engine Control Unit (ECU) of the vehicle gave the instantaneous engine status and the parameters necessary to calculate the engine work and auxiliary signals such as vehicle speed, engine speed and torque, etc.

Table 5. Characteristics of the equipment. The span range used (not the maximum of the instrument) for the PEMS is also given. Note that the laboratory grade analysers have many ranges and select automatically the appropriate one.

Technology	PEMS	Laboratory (tailpipe and diluted)
Gas analyzers		
Manufacturer	Sensors Inc.	AVL GmbH
Model	Semtech-DS	AMA i60
CO_2 principle (range)	NDIR (14%)	NDIR
CO principle (range)	NDIR (3000 ppm)	NDIR
NO principle (range)	NDUV (2000 ppm)	CLD
NO_2 principle (range)	NDUV (500 ppm)	CLD
Total HC (range)	FID (250 ppm)	FID
Exhaust flow	EFM pitot 4 inches	CVS – dilution air
PN analyzers		
Manufacturer	HORIBA	Testo
Model	Mod. NPET (Nanoparticle Emission tester)	Nanomet 1
Thermal pre-treatment	Catalytic stripper (350°C)	Evaporation tube (350°C)
Detection principle	CPC 23 nm	CPC 23 nm and 10 nm

NDIR: Non-dispersive infrared detection; CLD: Chemiluminescence detection, NDUV: Non-dispersive ultraviolet; FID=Flame ionization detector; EFM: Exhaust flow meter; CVS=Constant volume sampler; NPET=Nanoparticle tester; CPC=Condensation particle counter.

Source: JRC, 2019 [**20**]

The laboratory tests were conducted on the 2-axis roller dynamometer of the Vehicle Emissions Laboratory (VELA 7) of the Joint Research Centre (JRC) [**25**]. The exhaust gas was connected to the full dilution tunnel with a 9 m tube (the last 4 m insulated). The full dilution tunnel with constant volume sampler (CVS) was used with a flow rate of 100 m^3/min. With this flow rate at least a dilution ratio of 6:1 was achieved, even for the highest loads.

Gas analysers (AMA i60, AVL List GmbH, Graz, Austria) [**26**] at the tailpipe and the dilution were used (details in **Table 5**). They measured hydrocarbons (HC) with a FID (Flame ionization detector), NO_X ($NO+NO_2$) with a CLD (Chemiluminescence detection), and CO and CO_2 with a NDIR (non-dispersive Infrared) analyser respectively. They had multiple ranges to determine accurately (typically within 2%) the concentration of the gases.

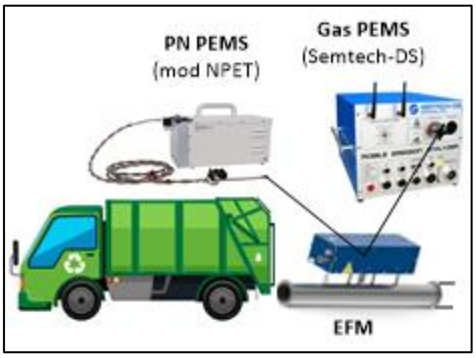
Particle Number (PN) measurements were performed using a Nanomet 1 (ViPR) system [**27**]. This consists of an MD19-2E rotating disc diluter followed by an ASET15-1 thermodiluter. The sample is diluted 40:1 at the sample point with the rotating disc diluter using filtered air at 150°C. The diluted sample is then thermally treated at 350°C in an evaporating tube and subsequently diluted in a simple air mixer diluter at a rate of 4:1. A TSI 3790 CPC [**28**] having a 50% counting efficiency at 23 nm and an Airmodus (Helsinki, Finland) A20 CPC [**29**] modified by the supplier to achieve a 50% counting efficiency at 10 nm were used to measure the solid PN concentration.

Additional pollutants, including ammonia (NH_3) and nitrous oxide (N_2O) were measured with a Fourier-Transform Infrared Spectroscopy (FTIR) instrument (Sesam i60 from AVL) [**30**] connected to the vehicle tailpipe, using a heated polytetrafluoroethylene sampling line (191 °C).

For both vehicles, the (empty) mass of the vehicle was around 15500 kg. The mass of the refuses was approximately 4700 kg. The total mass including instrumentation and 3 persons was around 20500 kg. The simulated mass of the vehicle on the chassis dynamometer was 20800 kg which represented a 50% payload as it was required in the in-service conformity heavy-duty emissions regulation. The road load coefficients were estimated based on previous similar vehicles.

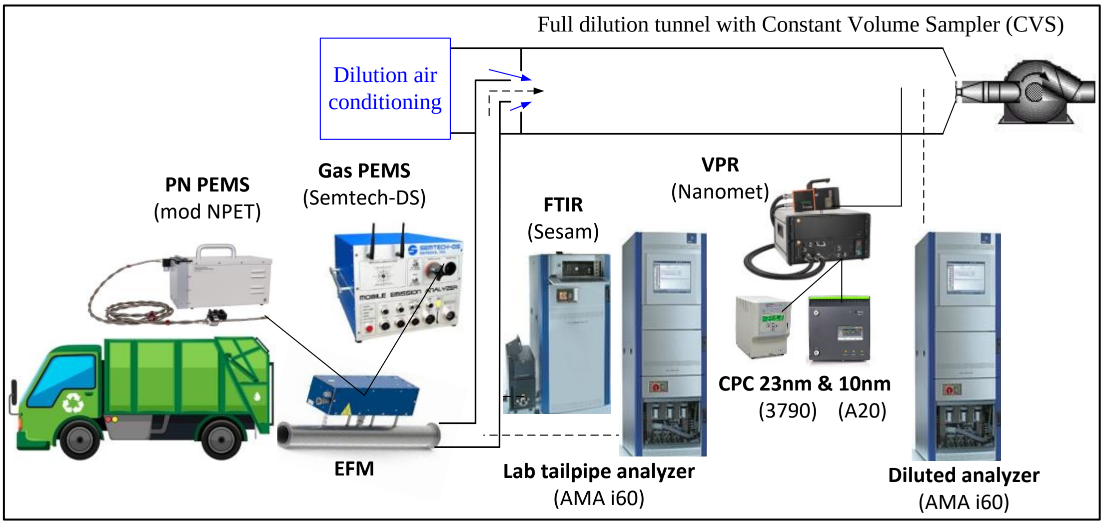
The following figures give a general overview of the experimental setup in the road test (**Figure 13**) and in laboratory test (**Figure 14**).

Figure 13. Road instrumentation configuration (PEMS=Portable emissions measurement system; PN=Particle number; EFM=Exhaust flow meter).



Source: JRC, 2019

Figure 14. Experimental laboratory instrumentation set up (PEMS=Portable emissions measurement system; PN=Particle number; EFM=Exhaust flow meter; VPR=Volatile particle remover; CPC=Condensation particle counter).



Source: JRC, 2019

3.5.2 Test Methodology

Calculation and analysis

The PEMS and the laboratory automation system calculate the emissions in g/s (or particles/s) with all requirements described in the regulation (background correction for CVS, zero drift correction for PEMS, dry-to-wet correction (approximately 0.95), time alignment etc.) (see also [**21**] for more details). No NO_X humidity correction was applied in order to present real ambient NO_X emissions (approximately 0.95). The different parts of the cycle were integrated and divided by the distance or work for the specific part. The work was calculated by the revolutions and torque provided by the ECU as required in the regulation. The measurements at the dilution tunnel have less uncertainty because they are close to what the regulations require. The measurements at the tailpipe have slightly higher uncertainty usually due to the uncertainty of the exhaust flow measurement. For this reason, PEMS, tailpipe and FTIR were compared to the analysers at the dilution tunnel (See paragraph **4.2**, Validation of PEMS with dynamometer test cell). Since both vehicles were a Euro VI step C trucks, we decided to follow the guidelines provided by the Regulation(EU) 582/2011[**7**], even if not applying it in an integral manner. In detail, this methodology foresees the division in three different vehicle speed bins (U-R-M) using the so called "speed based" method, which consists in attribute the speed in the correspondent bin, wherever it happens. No order of the speed class is required. This approach, which is applied till the Euro VI step C vehicles, differs from the so called “First Acceleration” method, used starting from Euro VI-d vehicles, in which the bin changes after the first aggressive acceleration. In this case the order of the segment (U-R-M) is fundamental: it is not more possible to attribute a vehicle speed lower than 50 km/h to the urban bin after that a strong acceleration changed the bin from, e.g., “urban” to “rural”.

It was decided to perform the data analysis, taking into account the entire data set, without any boundaries exclusions, unlike has been defined in the regulation, since the purpose of the current study is not to evaluate the effectiveness of the current Euro VI HDV regulation framework, but to present to the extent possible the real world performance of HD vehicles in terms of their pollutant emissions.

Obviously, this approach will include in the analysis high emission events, which are representative of real world application of the vehicles. The results of these studies can be evaluated thanks to a positive outcome of the comparison of equivalent test routes, in terms of distance and large time consistency (see **Paragraph 3.4**.**4**).

Boundary conditions

The current PEMS procedure for HD vehicles defines a series of boundary conditions that should be considered when performing the emissions data analysis for regulatory purposes [**8**]. The most important limitations include vehicle conditioning (cold start data are not considered for coolant temperature < 70°C) and engine power operation. These conditions are normally excluded from the emissions dataset. Nevertheless, in our tests, we have preferred to start the engine operations with a coolant temperature in average of around 20°C for ISC tests, even lower in the CITY tests (real ambient conditions), which was closer to reality. The only test cycles which had foreseen higher cold start operations, a sort of warm up, is the CITY-SIM test (in the range 55-65°C). In addition, a separate analysis will focus on the impact of different cold start conditions, very far from the regulatory threshold (0°C and 20°C).

Furthermore, the Euro VI Regulation(EU)582/2011[**7**] foreseen that tests were performed with a payload within 50–60% of the vehicles maximum permissible load, as this payload is considered representative of the real-world application of these vehicles. However, even if emissions behaviour is largely affected by the payload, in our study, we tried to uniform the payload for both vehicle (Diesel and CNG) according to the test cycle, i.e. the same payload has been used for both vehicles in the same pattern. More precisely, we consider no payload for ISC_LIKE and ISC_COMPLIANT, as well as for CITY_SIM cycles. In the real urban cycle (CITY) the payload was represented by the garbage weight and, naturally, it was increasing during the waste collection. It is worthwhile to remind that the aim of the study was to provide a direct comparison methodology between the two types of vehicle, even with some discrepancy compared to the present regulation.

Tests were performed at a temperature range of 2–20°C. Environmental conditions were different during testing, in particular temperature and relative humidity varied very widely during the testing campaign (rainy, windy, cold or relatively warm days). It is clear that a direct comparison of emission factors between the two vehicles is not possible at 100%, since they were measured under different environmental conditions. Typically, at low temperature conditions the EGR rates are reduced and urea solution delivery in the SCR decreases or terminates [**31**]. However, no major effect to the EGR system is expected for this temperature range.

Routes

On-road tests were performed with the aim of recording real-world emission factors of gaseous pollutants from Euro VI HD vehicles. As already mentioned in the previous chapters (in particular on **3.4**), three different test cycles where selected. A route of approximately 200km with the same characteristic of an In-Service Conformity

(ISC) pattern (called ISC_LIKE), which consists of urban, rural and highway parts. In the ISC test cycle Urban driving is by definition linked to vehicle speeds lower than 50km/h, even if it seems to be very distant form reality, as these vehicles in an urban environment rarely exceed 30km/h, due to their size and the need for frequent braking. Route's statistics based on the vehicle speed are summarized in **Table 3** and **4** of the **3.4.4** section. Since the aim of the current study was not to run trips according to the requirements of ISC legislation, we chose a consolidate pattern already used in previous testing campaign to try to guarantee the maximum repeatability of the tests. Nevertheless, if the trip is suitably cut ISC_COMPLIANT), the trip sessions were not significantly distant from these of the regulation for N3 vehicles. Instead the ISC_LIKE tests, with an average of around 40% of URBAN part, is more oriented to a real driving test in city conditions. One of the aims of this study is to verify how far the ISC test, designed for Long-Haul HD trucks, is from the real-world operations. A comparison between ISC_LIKE and ISC_COMPLIANT will be addressed in a dedicated section (see **Chapter 5**).

The CITY_SIM is a test planned to be easily reproduced in the laboratory under conditions more closed to the real operation carried out in the city environment.

For ISC_LIKE/ISC_COMPLIANT and CITY_SIM tests, a minimum of three tests were performed with each vehicle in order to investigate the repeatability of on-road tests. In general, this type of testing is considered to be less repeatable compared to laboratory tests, therefore a minimum number of repetitions is required to ensure high quality results and analysis.

As regards the CITY_MILAN cycles in the metropolitan area of Milan, only two tests were performed for each vehicle. The choice was made not to hinder or delay the normal operations during the daily waste collection in the municipality of Milan.

3.6 Data handling procedures and tools during road tests

3.6.1 Test data

The parameters that had to be recorded are listed in **Table 6**. The unit mentioned is the reference unit whereas the source column shows the measuring methods that were used.

3.6.2 Time alignment

The test parameters listed in **Table 6** are split in 3 different categories:

- Category 1: Gas analyser (THC, CO, CO2, NO_X concentrations);
- Category 2: Exhaust flow meter (Exhaust mass flow and exhaust temperature);
- Category 3: Particle Concentration analyzer (PN in #/cm^3).

According to the procedure developed for heavy-duty engines, the time alignment of each category with the other categories has to be verified by finding the highest correlation coefficient between two series. All the parameters in a category are shifted to maximize the correlation factor.

The only possible parameters, which may be used to calculate the correlation coefficients to time-align Category 1 with Category 2 are using the CO2 concentration and the exhaust mass flow or the GPS data and exhaust mass flow (the latter only in some cases). To time-align the particle number, it has been used the PN concentration in #/cm^3 and the Exhaust Mass Flow signal from the EFM unit.

Table 6. List of main test parameters retrieved in the road tests and in the LAB (other details).

Parameter	Unit	Source
HC concentration (1)	ppm	PEMS/Analyser

CO concentration (1)	ppm	PEMS/Analyser
NO_X concentration (1)	ppm	PEMS/Analyser
CO_2 concentration (1)	ppm	PEMS/Analyser
PN (Particle Number)	$\#/cm^3$	NPET/APC
Exhaust gas flow	kg/h	Exhaust Flow Meter (hereinafter EFM)/CVS
Exhaust temperature	°K	EFM/sensor
Ambient temperature (2)	°K	Sensor
Engine Speed	rpm	ECU
Engine Torque	Nm	ECU
Coolant Temperature	°C	ECU
SCR Temperature (only Diesel)	°C	ECU
Oil Temperature	°C	ECU
Air Inlet Temperature	°C	ECU
Fuel Consumption	°C	ECU
Vehicle longitude	degree	GPS
Vehicle latitude	degree	GPS
Vehicle Speed	km/h	GPS/ECU

Notes

(1) Measured or corrected to a wet basis

(2) Use the ambient temperature sensor or an intake air temperature sensor

Source: JRC, 2019

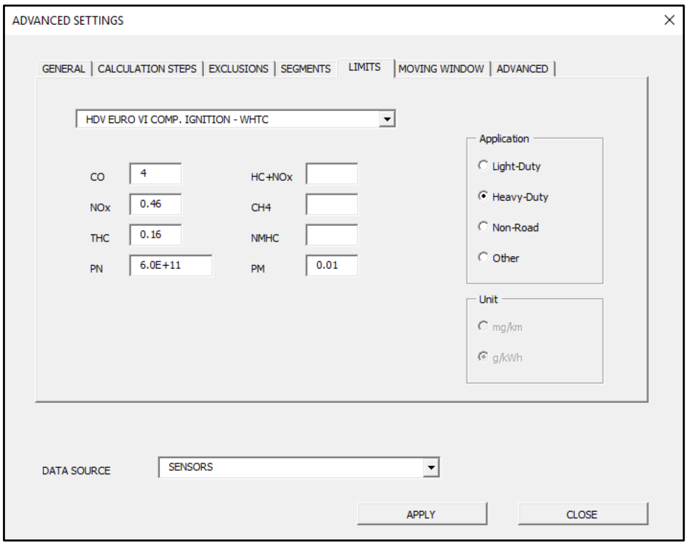
3.6.3 EMROAD©

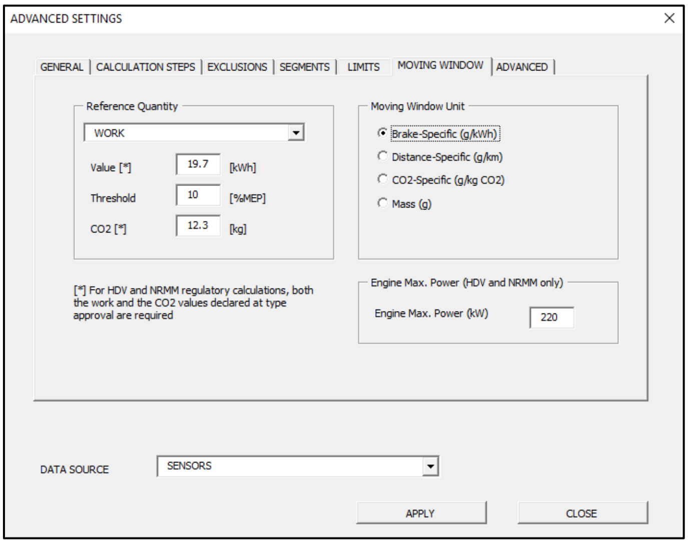
Reporting templates and an automated data analysis were used to ensure that all the calculations (of mass, distance specific and brake specific emissions) and verifications were done consistently throughout the testing program. The in-house developed excel add-in EMROAD© has been used (EMROAD release 6.03) for such automated data analysis (see **Figure 15** as example of EMROAD's setting interface forms).

The standardized reporting templates included, for every test:

- Second by second test data for all the mandatory test parameters;
- Second by second calculated data (mass emissions, distance, fuel and brake specific);
- Improved time alignment procedures between the different families of measured signals (analysers, EFM, engine);
- Data verification routines, using the duplication of measurement principle, to check for instance the directly measured exhaust flow against the calculated one;
- Averages and integrated values (mass emissions, distance, fuel and brake specific).

Figure 15. EMROAD setting interface forms.





Source: JRC Vela, 2019

3.6.4 Data screening principles

The calculations and the data screening were carried out using EMROAD©.

4 PEMS equipment

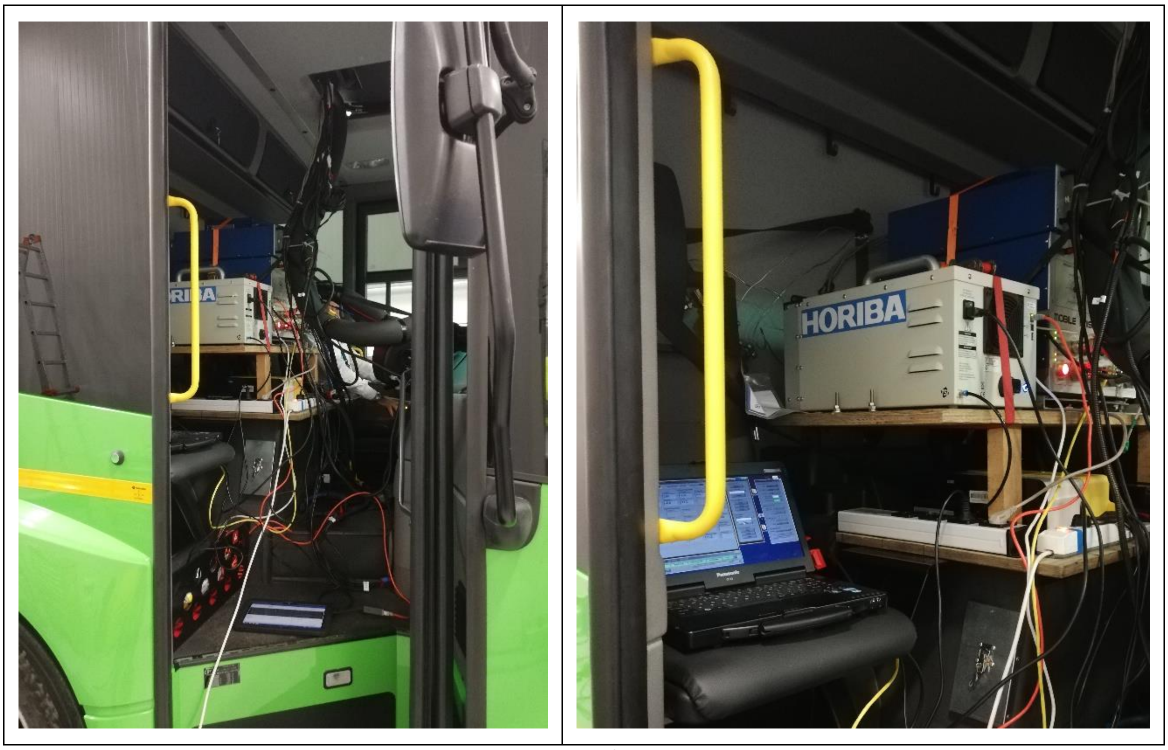
The lessons learned from the AMSA testing campaign can be summarised as follows.

4.1 Installation of PEMS equipment

The following is a non-exhaustive list of suggestions/recommendations extracted from the experience obtained in the field during the test program.

1. Installation of instruments should be made on a stable plate. The gas analyzer should be mounted using suitable damper to reduce the vibrations and shocks (see **Figure 16**);
2. Some degrees of freedom needs to be allowed for the EFM connection to the tail pipe, i.e. allow the instrument to move slightly without risking to damage tubes, cables (slack) and connections (military type), to compensate for vibrations and high accelerations (see **Figure 17**);
3. Instruments can be installed in the vehicle cabin using a stable platform (See **Figure 16**). The battery pack can be installed in different positions: in either in the roof of the truck or in some side spaces, as shown in **Figure 18**, according with the space at disposal. In our case, an additional plate with appropiate brackets has been introduced in the layout;

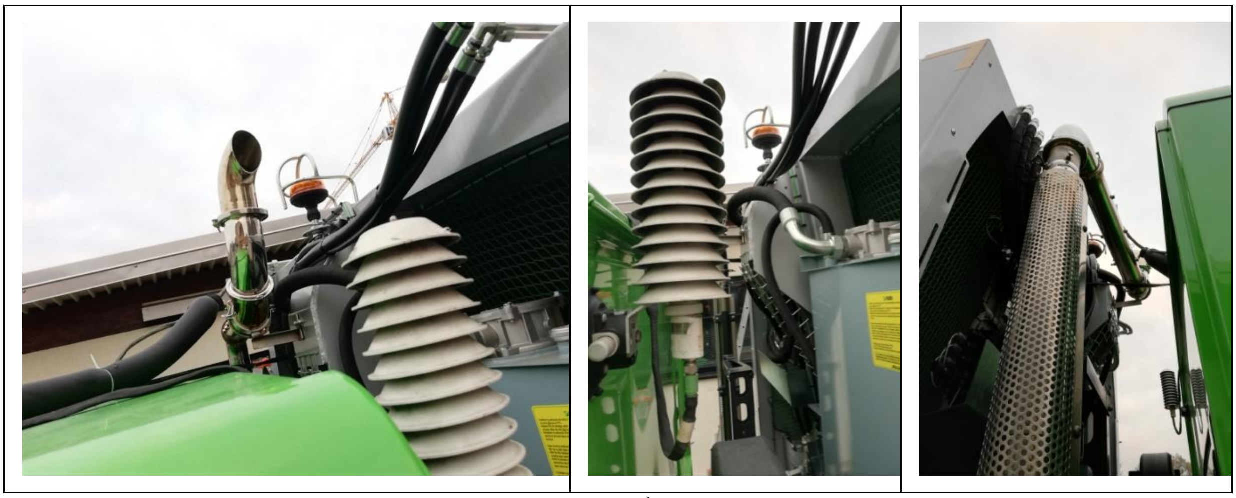
Figure 16. Mechanical works necessary to safely installing the PEMS instruments (gas analyser and NPET).



Source: JRC Vela, 2018

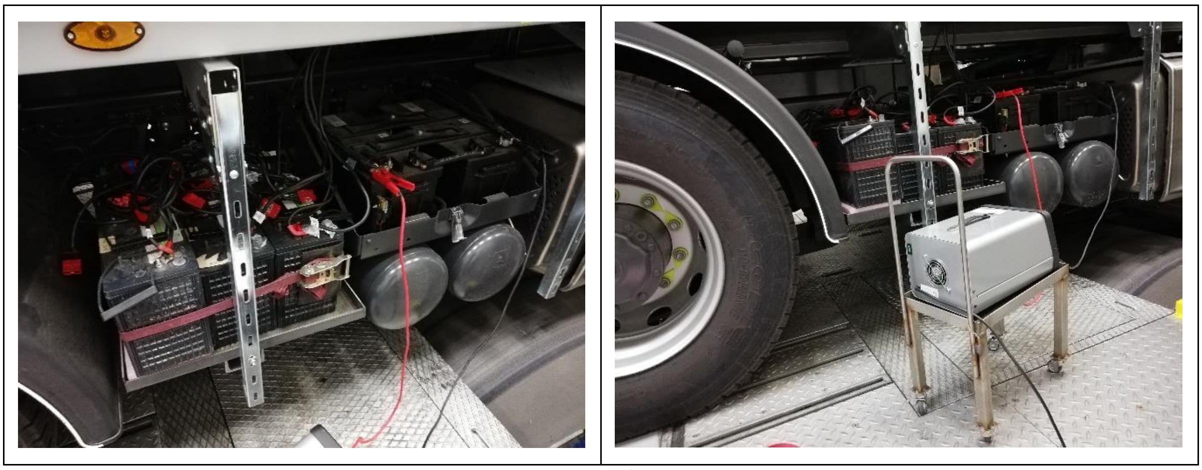
4. Due to the outline of the cabin, installing the equipment onto the platform of the vehicle can prevent access to the gas analyzer components (e.g FID fuel bottle, filter);
5. For safety reasons, the equipment need to be secured to the platform istself: straps are considerated a good solution (see **Figure 16**);
6. Permanent machinery modifications must be avoided as those will not be acceptable to the vehicle owner;

Figure 17. EFM and the ambient probe installation.



Source: JRC Vela, 2018

Figure 18. Mechanical works necessary to safely installing the auxiliary battery pack.



Source: JRC Vela, 2018

7. Access to the test equipment is necessary – either for the installation or for the checks between the tests –. Safety aspect needs to be considered;

8. Minimum power required: batteries BUT the batteries have a limited autonomy and need to be replaced or recharged. The replacement is difficult because of their weight (~30 kg), therefore the use of Gel batteries are recommended or more advanced battery chemistry (e.g. Li-ion batteries);

9. Field testing: span gas bottles must be taken to the field to zero-span the gas analyzers, unless the measurements start from and finish in a workshop (CITY_SIM and ISC did not present this eventuality. Instead it was an issue for the CITY test in Milan. In case of gas cylinder handling a European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) certification is always needed;

10. Avoid contamination of the air used to zero the gas analyzers (by the engine itself, the power generator or any other source);

11. Recommendation: Remote monitoring of the instruments using Wifi;

12. Recommendation for the laptops: they need to be ruggedized, for high autonomy, dust and water proof, lighting of the monitor, etc.

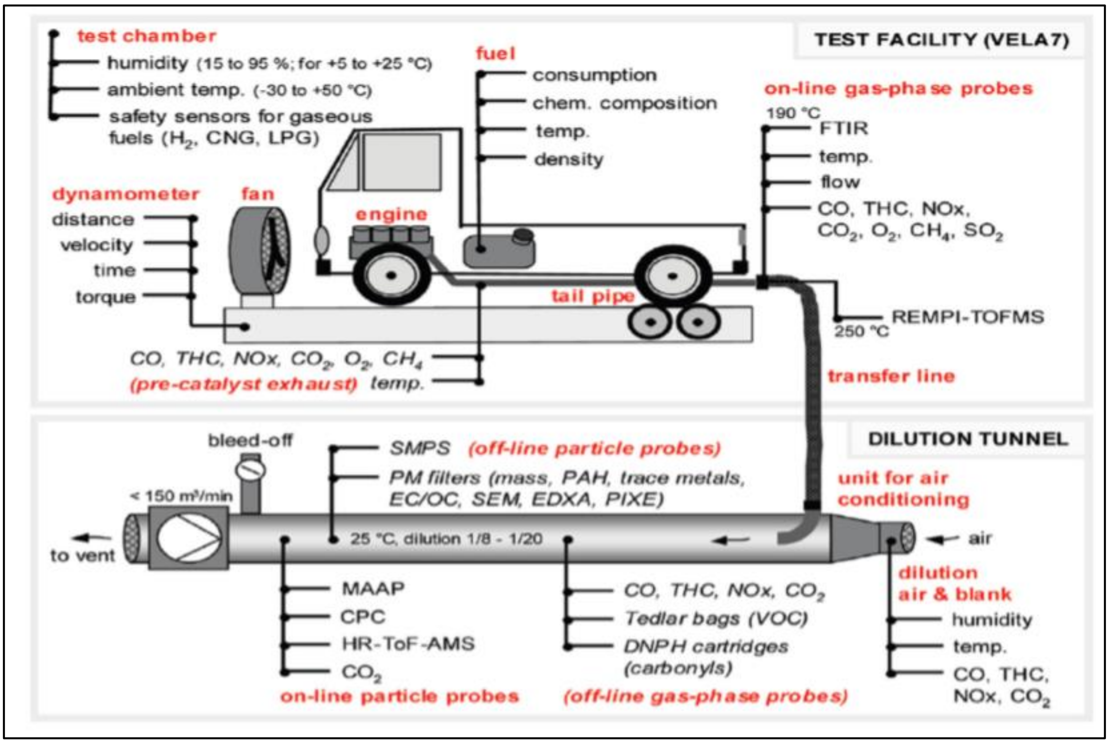
4.2 Validation of PEMS with dynamometer test cell

The PEMS uncertainty has already been assessed by many researchers. In USA, the measurement allowance study found a NO_X uncertainty (allowance) of 600 mg/kWh for 2007–2009 engines, which was around 23% of the 2007 standard [**32**, **33**]. The NO_X allowance for post 2010 engines was found to be 200 mg/kWh, which was over 60% of the 2010 Not-To-Exceed standard [**34**]. A recent study at 20 mg/kWh levels found 10 mg/kWh measurement error (50%) [**34**]. In EU, an uncertainty of approximately 45% at 80 mg/km levels was found (33 mg/km) assuming a drift of 5 ppm [**35**]. Thus, our older generation PEMS is between older PEMS assessments and the newer generation PEMS results (see more detail in **Annex 4**).

In order to assess the uncertainty of the measurements, the PEMS was compared with laboratory grade analysers on a chassis dynamometer. Additionally, the same on-road cycles were retested in the laboratory in order to investigate possible discrepancies between real world emissions and laboratory testing [**36**]. The assessment of PEMS instruments was carried out at the Vehicles Emissions laboratory (VELA) of the Suistainable Transport Unit, Directorate for Energy, Transport and Climate, European Commission – Joint Research Centre(JRC), located in Ispra, Italy.

The PEMS was compared to the laboratory equipment during the chassis dynamometer tests performed in Vela 7 (See **Figure 19, 23** and **24**). [**37**]

Figure 19. VELA 7 Test facility overview (LAB test configuration).

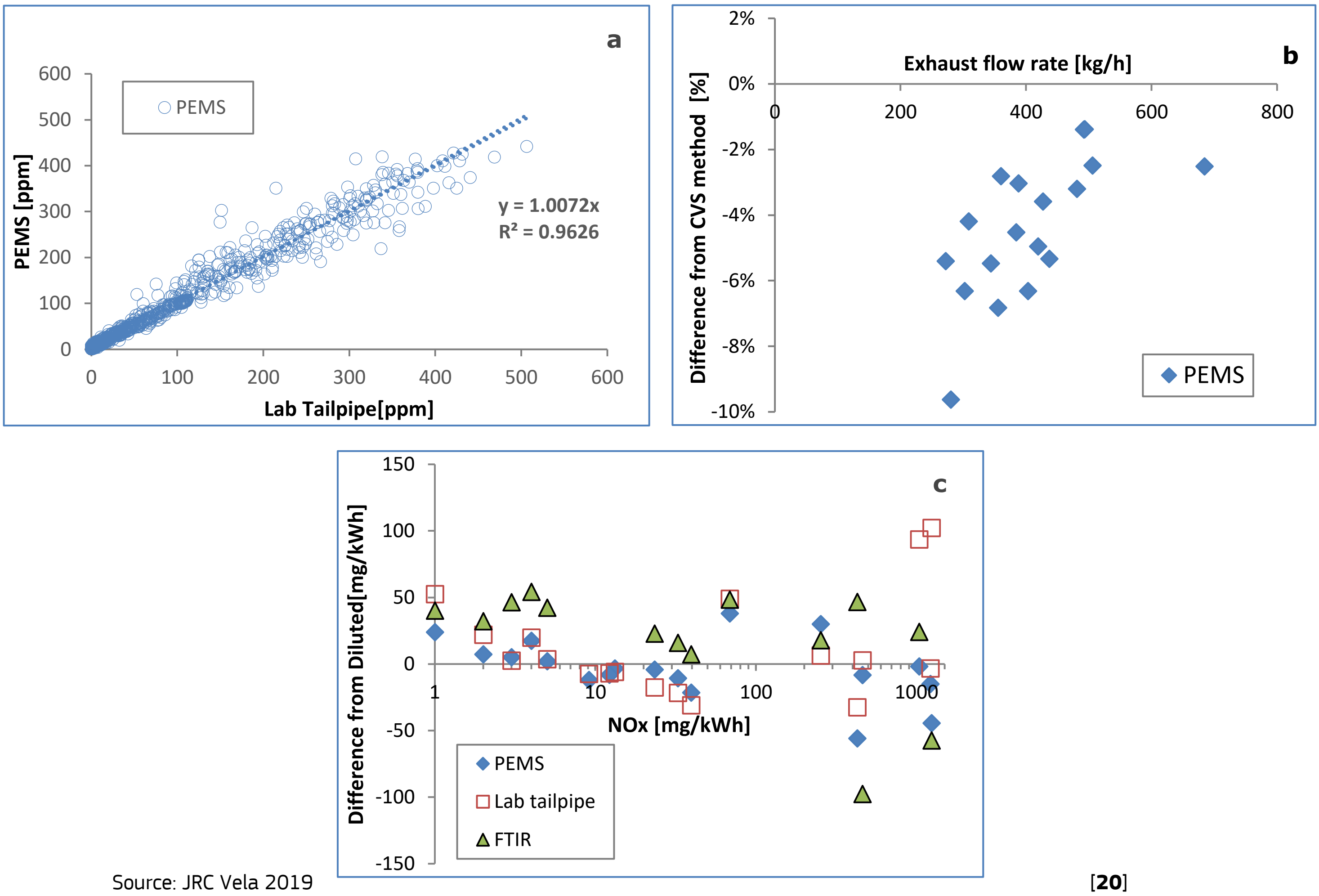


Source: JRC Vela, 2016 [**37**]

Figure 19 presents an overview of the VELA facility and equipment used for HDVs emission and performance testing. The chassis dynamometer is designed to host HD vehicles up to 30 tons in weight and 12m in length. Maximal test speed is 150 km/h. The test cell can be conditioned between -30and +50 °C with relative humidity in the range 15-95%. The CVS (Constant Volume Sampler) for full exhaust dilution is equipped with 4 Venturis of 10, 20, 40 and 80 m^3/min in order to achieve a maximum air flow of 150 m^3/min. Dilution air is taken form test cell, conditioned to 22 °C, and filtered through high-efficiency particulate air and activated charcoal filters. The VELA7 climatic test cell has an air circulation system that provides enough number of cell changes (≥15).

Figure 20 summarizes the results for the exhaust flow measurements and NO_X for the Diesel engine vehicle. The NO_X concentration in ppm between PEMS and VELA_7 laboratory grade equipment (Lab Tailpipe analysers) was linear with a very good correlation and R-squared value (coefficient of determination), indicating an average difference less than 1% (see **Figure 20a,** in which a ISC_LIKE test is showed). The exhaust flow meter (EFM) of PEMS is around 4% lower than the estimated flow by the dilution tunnel (total diluted flow minus dilution air flow) (**Figure 20b**). The comparison of the gas PEMS with the laboratory analysers (see **Figure 20c**) (called "validation" in the light-duty real-driving emissions (RDE) regulation) gave differences within 50 mg/kWh for NO_X. In addition, the NO_X results from the FTIR and laboratory tailpipe analysers are given. They had similar or slightly higher differences when compared to laboratory analysers. In fact, their differences to the dilution tunnel analysers were also typically within 50 mg/kWh, with a few exceptions that reached 100 mg/kWh. The emissions of CO, HC and PN in Diesel vehicle were very low, close to the detection limit of the instruments and no figure is shown. Our results were corrected for zero drift (approximately 50-100 mg/kWh) [**20**], something permitted in the heavy-duty regulation, but not in the light-duty one. Note that a 5 ppm drift which was equivalent to an error of <25 mg/km for light-duty vehicles, for a city refuse collection cycle of a heavy-duty vehicle can reach 250 mg/km; more than ten times higher than the light-duty value due to higher exhaust flow rates and shorter distance covered. While the PEMS were corrected for the zero drift, following the same approach, the diluted values were corrected for the NO_X background levels.

Figure 20. Diesel vehicle PEMS assessment **a**: Comparison of PEMS NO_X concentration in ppm; **b**: Comparison of PEMS exhaust flow meter (EFM) with dilution tunnel (CVS) based estimation of exhaust flow rate; **c:** Comparison of PEMS, FTIR and laboratory grade tailpipe analysers with dilution tunnel (CVS) analysers for NO_X. Each point is one test of a part (phase) of a testing cycle.

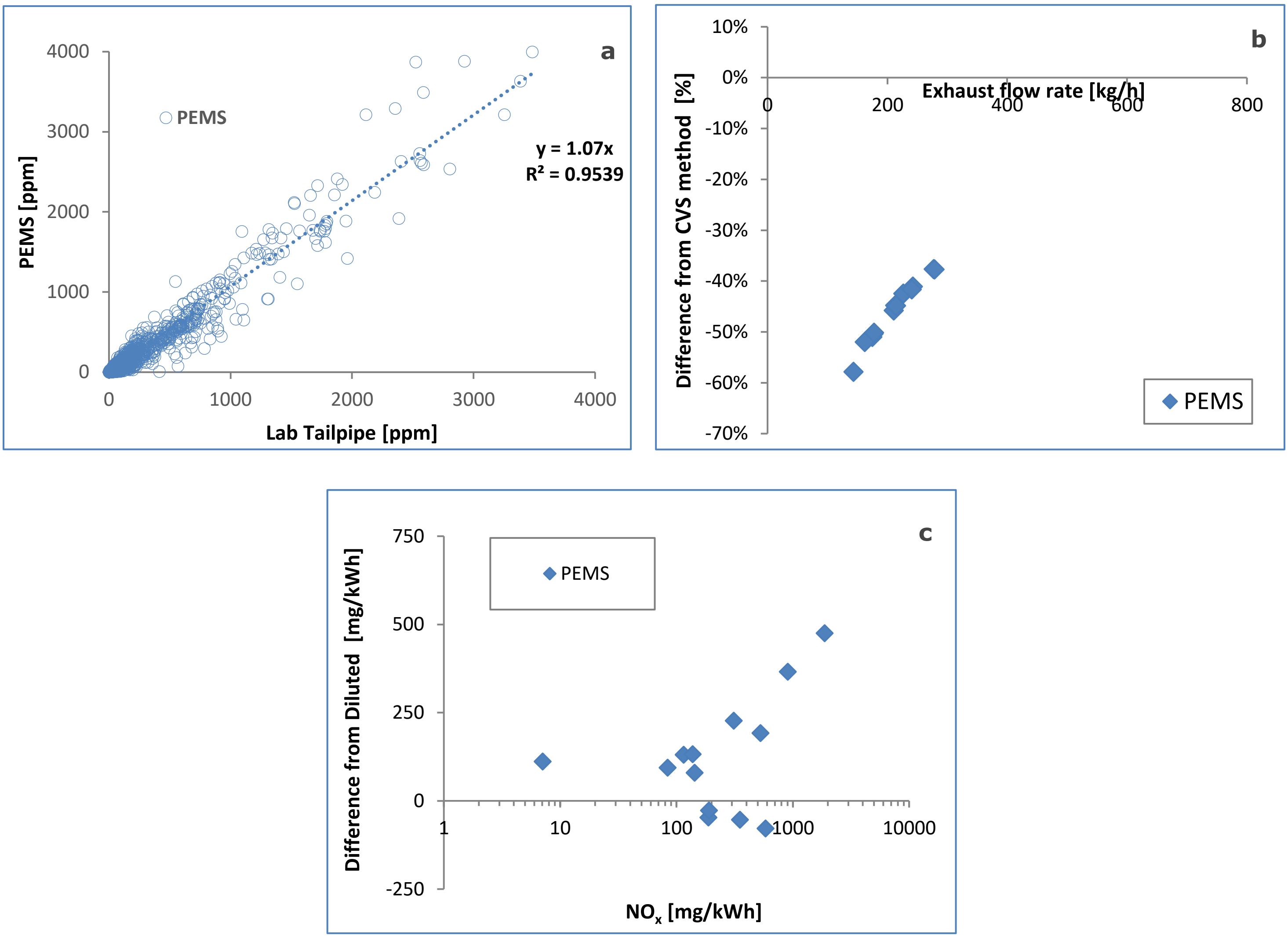


Source: JRC Vela 2019 [**20**]

Same validation has been proposed also for CNG vehicle in **Figure 21**. While the NO_X concentration in ppm correlation between PEMS and VELA_7 laboratory equipment (Lab Tailpipe) remained in a very good is linear correlation with an average difference of around 7% (see **Figure 21a,** in which a ISC_LIKE test is showed). Unfortunately, the same good results were no common also to the emission mass flow. **Figure 21b** shows a huge average distance from CVS method, in fact the exhaust flow meter (EFM) of PEMS is around 40/50% lower than the estimated flow by the dilution tunnel (total diluted flow minus dilution air flow), with a very massive underestimation of the exhaust mass flow. Obviously the same trend was detected also analysing the emission factors in g/kWh, as the mass emission is governed by the exhaust flow mass rate. In fact, the NO_X brake specific linear correlation between FTIR or laboratory grade tailpipe analysers and PEMS equipment, returning the same values, namely an average difference between 40-50%. Their differences to the dilution tunnel analysers were also typically within 250 mg/kWh, with a few exceptions that reached 500 mg/kWh, on average 5 times higher than in the Diesel vehicle (see **Figure 21c** for reference).

No figure is shown for the emissions of CO, HC and PN for the Diesel nor for the CNG vehicle, however they have similar behaviour to the case of NO_x.

Figure 21. CNG vehicle PEMS assessment **a**: Comparison of PEMS NO_X concentration in ppm; **b**: Comparison of PEMS exhaust flow meter (EFM) with dilution tunnel (CVS) based estimation of exhaust flow rate; **c:** Comparison of PEMS with dilution tunnel (CVS) analysers for NOx. Each point is one test of a part (phase) of a testing cycle.



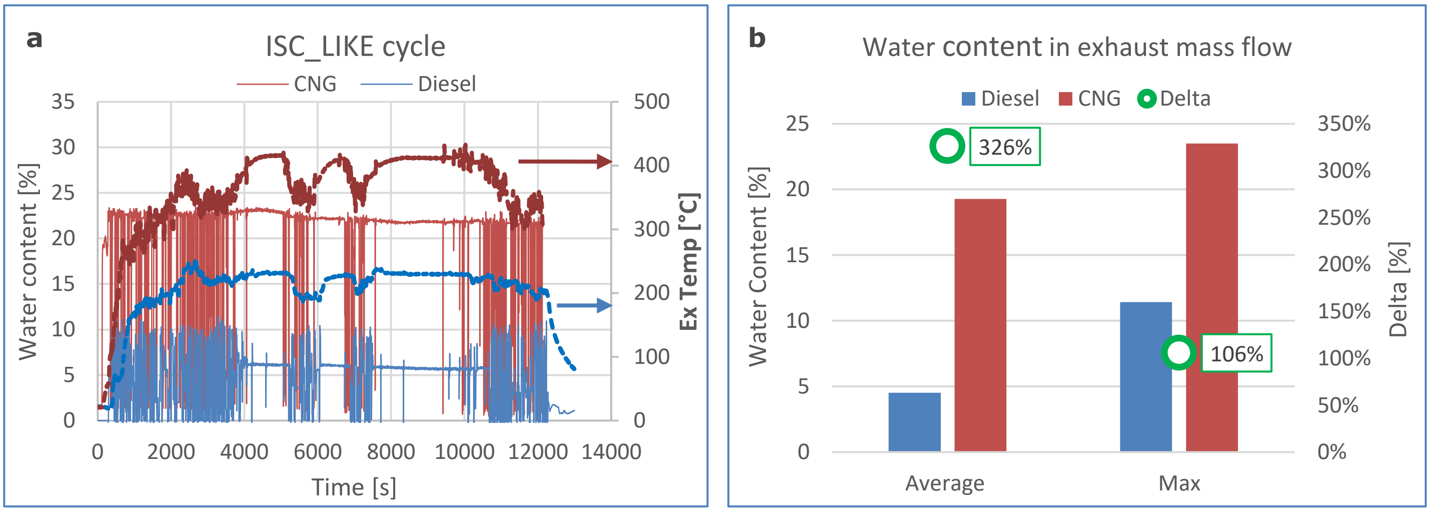
Source: JRC Vela, 2019

The reason is to be found in the fact that, during the testing cycles, the CNG truck generated a higher concentration of condensable water vapour than the Diesel one, that is the main cause that supposedly gave us a considerable error in the direct measurement using an EFM based on a Pitot tube. **Figure 22** depicts the significant difference in the water vapour content between the two means. The Diesel vehicle produced on a ISC_LIKE cycle an average of 4.53% of condensable water vapour content. The CNG 19.28%: more than 3 times. A big gap was also recorded in the maximum values: 11.42% vs 23.50%, more than double (see **Figure 22b**). For completeness of information, in **Figure 22a**, the exhaust temperature profile has been added in the secondary vertical axis using a dotted line and a darker tonality. The effect of high concentration of water vapour content on the exhaust mass measurement, using flowmetering techniques based on pitot tube, will not be a subject of this report, however it could be addressed in future works.

A technical basis could be sought in the nature of the two fuels (a molecule of Methane contains more hydrogen than a corresponding molecule of Diesel fuel), as well as in the presence of after-treatment devices with opposite characteristics. Highly hydrophilic the SCR unlike the TWC.

According to our findings a correction of the exhaust mass flow would seem recommendable. In this report, we have analysed the emissions without taking into account any correction of the flow nor for Diesel neither for CNG vehicle. The choice was to present the real measured data as we were underestimated the emission factor values. This was a conservative approach, since the error committed was from the safe side (gave us a safe margin), considering that we have proposed a threshold given by the reference limits, as we have introduced in the rest of the discussion (see **Chapter 5**). Namely, we preferred to underestimate, rather than overestimate applying a correction that, even based on experimental evidences, could make us take the risk of exceeding the above limits in case of a slightly higher adjustment.

Figure 22. Condensate water vapour content in percentage at the exhaust flow in correspondence of the PEMS probe. **a:** ISC_LIKE example cycle; **b:** Average and maximum content in the ISC cycle.



Source: JRC Vela, 2019

In a dedicated chapter (**Chapter 6**) a correction will be proposed and applied on some relevant cases.

Figure 23. View of JRC VELA_7 during preliminary comparison test and PEMS assessment.

Source: JRC Vela, 2019

Figure 24. View of JRC VELA_7 control room during laboratory tests.

Source: JRC Vela, 2019

5 Results and analysis

The tests showed that while the Diesel engines was fully compliant with past, current and near future regulations as it fulfilled the limits even when including cold start and under different test cycles, on the same basis and using the same considerations, the CNG engine showed some difficulties in particular regarding NO_X emissions in the CITY cycles and regarding the PN emitted during the ISC_LIKE cycle. This behaviors and tendencies will be deeply explored on the next paragraphs, where all the pollutants will be analyzed individually, paying close attention to the different phases of the tests, which will help us to better explain the overall outcome.

Another point that is essential to highlight is the fact that the limits proposed by Regulation Euro VI, refers only to a laboratory transient cycle which is applicable only to the engine, the so called WHTC (World Harmonized Transient Cycle) performed during Type Approval (TA), namely the homologation stage. See detail in **Chapter 6** and **Annex 1.** The TA test consists of two subparts: a cold WHTC and a hot WHTC cycle. The cold is weighted at 14% of the overall result. In the present study, the cold start is included and this choice worsened the final results giving higher total values for all pollutants. Obviously, the more affected are the NO_X, THC and PN.

Since it is quite complicate to extrapolate a suitable limit for the field evaluation, in which the vehicle -not the engine- is under investigation, we chose the same line proposed by the Regulation(EU) 582/2011[**7**], which prescribes to additionally apply, in the ISC test, a multiplication factor of 1.5 to the TA limits of gaseous pollutants [**20**]. In reality, this factor has to be used only in the evaluation of the Conformity Factors (CFs) and its validity is limited only to the Moving Average Window approach (see **Annex 5** for further details) and not on the average over the entire trip. The Conformity Factors in the RDE and in ISC test, respectively for light-duty and heavy-duty vehicles, give a concrete measure of the possible distance of the real emission factors from the laboratory values (e.g. at Type Approval), taking into account the difference of the measuring equipment, the variability of operations, as well as a number of boundary conditions not present in the laboratory, which inevitably make the test more severe. Even if not directly linked, nevertheless, we have enlarged this concept, adopting the same approach not only for the ISC cycles, but also for the other test cycles (CITY_SIM and CITY_MILAN). This new reference limit set has been called ROAD limits. Theoretically, neither measurement nor any additional factor (ROAD limit) are foreseen for PN at Euro VI step C, in spite of this, in view of a future regulation step, we have introduced not only the PN measurement, as prescribed in Euro VI step D, but also a reference threshold similar to the one foreseen by Euro VI step E in the conformity factor evaluation, namely a factor of 1.63. Refer to **Annex 3** for further details related to the difference of the Euro VI regulation steps.

In **Table 7** and **Table 8** are included the type approval values of the Diesel/CNG engine and the ISC measurements of the respective vehicles. Even though the two values are not directly comparable, they are quite close. In any case, the consistency of the values shows the proper operation of both engines.

Table 7. Official type approval values (TA) of Euro VI Diesel engine (25°C) and in-service conformity (ISC) results of the vehicle (2-20°C). For ISC testing a conformity factor of 1.5 and 1.63 additionally applies respectively to the limits of the gaseous pollutants and PN.

	CO [mg/kWh]	NO_X [mg/kWh]	HC [mg/kWh]	PM [mg/kWh]	PN [#/kWh]
Regulated limit	4000	460	160	10.0	6×10^{11}
TA engine (WHTC)	166	197	10	1.6	not available
ISC vehicle	735-840	87-190	0-1	not measured	$1\text{-}3\times10^{10}$

Source: AMSA, 2018; JRC, 2019

Table 8. Used type approval values (TA) of Euro VI CNG engine (25°C) and in-service conformity (ISC) results of the vehicle (2-20°C). For ISC testing a conformity factor of 1.5 and 1.63 additionally applies respectively to the limits of the gaseous pollutants and PN.

	CO [mg/kWh]	NO_x [mg/kWh]	HC* [mg/kWh]	PM [mg/kWh]	PN [#/kWh]
Regulated limit	4000	460	500	10.0	6×10^{11}
TA engine (WHTC)	502	171	17	1	not available
ISC vehicle	240-270	60-100	120-230	not measured	$5\text{-}7\times10^{11}$

*For CNG both NMHC (0.16 g/kWh) and CH_4 (0.5 g/kWh) are regulated. During this testing campaign it was not possible measured CH_4 separately, so we have considered the hydrocarbon (HC) as composed essentially by Methane and consequently the limit used is the only the CH_4 one.

Source: AMSA, 2018; JRC, 2019

See **Annex 1** for a detailed overview of the Type Approval limits during the heavy-duty engine homologation test (TA).

One of the main purposes of this study was to explore the concerns of various researchers regarding the emissions of Diesel and CNG refuse trucks. Diesel vehicles has always had a worse performance when compared directly with CNG vehicles. While this fact is correct for vehicle TA under Euro V Regulation, it becomes less clear when talking of Euro VI.

In the present chapter, the emission factors will be presented using both approaches and both methodologies: distance specific emissions in mg/km, as well as brake specific emissions in g/kwh. The latter one will be the reference one, as it is the same metric of the emission limit thresholds.
The emissions looked higher expressed in mg/km (see **Figure 26, 27 and 28** for reference), however, in some cases modern engines can have high emissions in the city even when expressed in mg/kWh [**17**]. Cold start and/or some city conditions (e.g. traffic/congestion) result in high engine out emissions (e.g. [**38**]) and low exhaust gas temperature and consequently the after-treatment devices (SCR, DOC, DPF and TWC for Diesel and CNG engines respectively) do not or partially work. As expected, in our testing campaign, the emissions were particularly high during cold start and during the waste disposal collection operation, where continuous stops were the rule (see **Figure 27** and **28**). Work-based emissions that are low can be high as distance-specific emissions if the work to distance ratio (W/D) is high (see **Table 3** and **4** as reference for the W/D ratio). Emissions are expressed per km typically for emission inventories, even though it is not applicable to heavy-duty engines and vehicles.

5.1 Overall results

Emission factors of all pollutants are given both as brake specific (i.e. mass per kWh of engine work output) similar to the metrics used in the Type Approval standards - that means the engine certification emission standards- and in mass per km covered by the vehicle (distance specific). In addition, an overview of the breakdown of pollutant emissions over the different phases (e.g. Urban, Rural and Motorway for ISC cycles) of the trip was performed, providing also the respective graphs. Where applicable, error bars, corresponding to the standard deviation of the averaged measurements, are provided. A synoptic panel of the emission factors of all pollutants for the two vehicles tested both in g/kWh and in g/km is also provided. The analysis mentioned above are made for each pollutant.

Since both vehicles were Euro VI step C trucks, we decided to follow the guidelines provided by the Regulation(EU) 582/2011[**7**], even though not all applicable boundary conditions were taken into consideration. For instance, no threshold for mean power demand was taken into account for the current ISC pass-fail evaluation. In all the cycles, the engine powers involved were below what normally expected in the ISC, so we were quite far from the standard conditions of an ISC test.

Even if in Euro VI step C the cold start is not included, we took it into account as it covered the majority of the emission events. Furthermore, the cold Start is considered in the next amendment (Euro VI step E) during In-Service Conformity tests. As previously mentioned, the solid particle (PN) were measured even if not prescribed by the Euro VI step C. They will be mandatory only starting from the Euro VI step E [**39**]. The cold start part was assessed individually, but it was also included in the urban and could be partially contained in the rural part (limited only to some routes) of the different cycles.

In detail, the Euro VI step C methodology foresees the division in three different vehicle speed bins (U-R-M) using the so called "speed based" method, which consists in attribute the speed in the correspondent bin, wherever it happens. No order of the speed class is required. This approach, which is applied till the Euro VI step C vehicles, differs from the so called “First Acceleration” method, used starting from Euro VI step D vehicles, in which the bin changes after the first aggressive acceleration. In this case the order of the segment (U-R-M) is fundamental: it is not more possible to attribute a vehicle speed lower than 50 km/h to the urban bin after that strong acceleration changed the bin from, e.g., “urban” to “rural”. In ISC_LIKE cycles the sharing time of the speed classification foreseen by the legislation (Euro VI step C) has not been respected. Thanks to a large timing consistency among the equivalent test routes, the results of these studies could be evaluated using a direct comparison base (see **paragraph 3.4.4**).

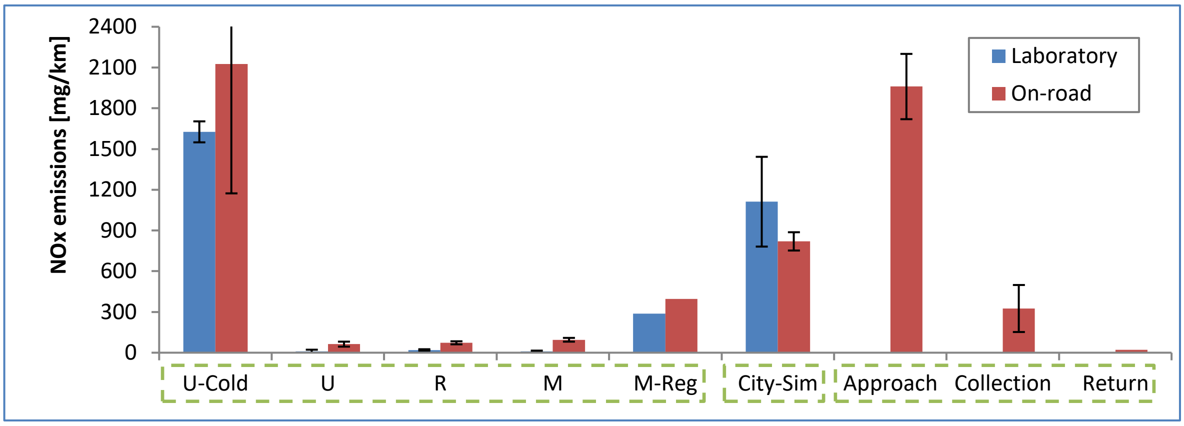
Figures 26, **27** and **28** depict the vehicle integrated emissions including cold start expressed in specific brake emission in mg/kWh or #/kWh (panel **a**) and in distance specific emission in mg/km or #/km (panel **b**).
The results referred to the complete cycle taking into account all the predicted phases, for instance Urban, Rural and Motorway parts in ISC_LIKE tests. No data exclusion has been used: all the events has been considered. The pollutant considered were only the regulated ones that are been measured in the testing campaign, this means, i.e. CO, NO_X, THC and PN. For every different cycle type, a minimum of two repetitions has been performed. The graphs below the average values are reported. The ISC_LIKE cycles has been executed starting with a coolant temperature of 20°C, so in cold conditions, as well as the CITY test (T coolant 2-14°C), in which no conditioning has been used. Instead, the CITY_SIM tests has been executed in a sort of hot condition, with coolant temperature, on average, around 60°C.

For graphical reason, to get an overview of all the above-mentioned pollutants, the CO values has been divided by a factor 10, while the PN values has been divided by 10^9. In some cases, the emission factors were very small to appear in the relative figures due to the scale of the graph itself. For instance, the emission values of THC of the Diesel truck.

To have a reference, also the limits for Type approval (TA limit) and a sort of equivalent field limit (ROAD limit) has been introduced. It is important to notice that not always the brake specific and the distance specific graphs have the same scale. It necessary to clarify that the HC limits are different, since the regulation prescribed diverse limits in case the engine is CI (Compression Ignition, namely Diesel) or SI (Spark Ignition, as Gasoline or CNG in our case). Respectively a total (THC) limit for of 0.16 g/kWh in CI engine and a double partial limit of 0.5 g/kWh for the Methane compounds and 0.16 g/kWh for the Non-Methane compounds in SI engines. As in a CNG vehicle, the hydrocarbon emitted at the tail pipe are principally Methane (>95-98%), we assumed that, for this vehicle typology, there was only a total limit coinciding with the Methane limit (0.5 g/kWh). This limit resulted indirectly much more severe than the regulated one, since we did not subtract the Non-Methane fraction from the total amount.

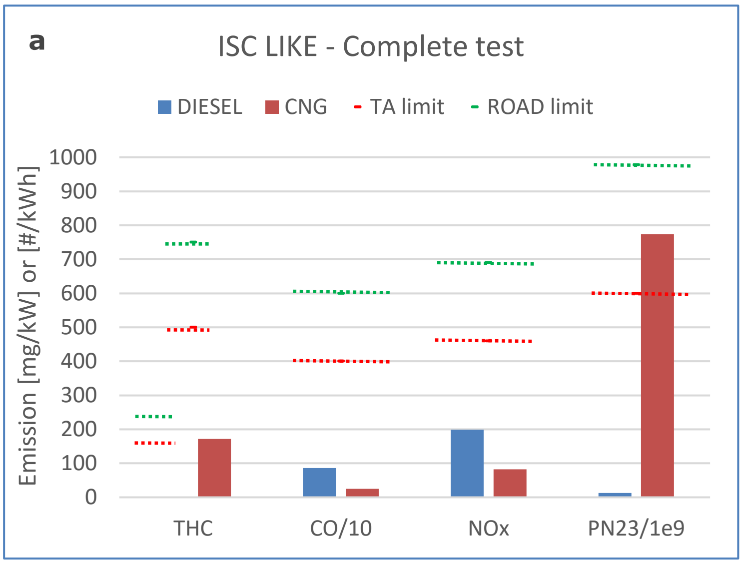
In **Figure 25**, NO_X emissions for the diesel vehicle is depicted. The error bars show max-min values of at least 2 repetitions, while dashed boxes indicate the complete cycle. The Cold (U-Cold) and Approach parts start with cold engine. The laboratory temperature was 20°C, while the ambient temperature at the on-road tests was between 2°C and 14°C. Although there were some not irrelevant differences, this showed that there was no large discrepancy between PEMS test performed in laboratory and on road, which once more states the reliability of the measures in real world using PEMS [**40**-**43**]. As expected, the differences are within a factor of 1.5. This additional multiplication factor is applied to the regulatory limits (called TA limit) only for the brake specific metric, anyway could be consider a reasonable factor extensible to all testing cycles (1.5 for gaseous pollutant and 1.63 for PN). The plotted values and the relative differences between laboratory and road tests for the NO_X case, have strengthened the belief that these reference limits were applicable, at least in principle, to all the cycles performed. Only a case from the Diesel vehicle has been presented just for reference. Same consideration could be done for CNG vehicle.

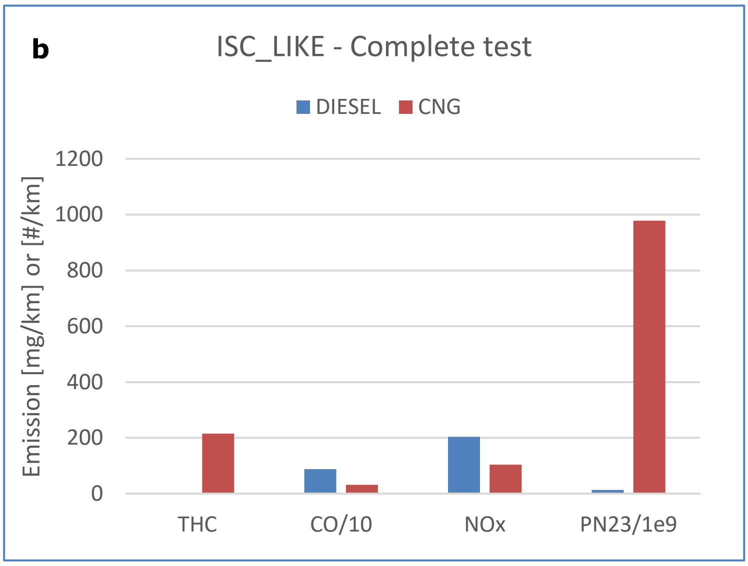
Figure 25. Diesel vehicle NO_x emissions measured with the PEMS in the laboratory (blue) and on the road (red).



Source: JRC Vela, 2019 [**20**]

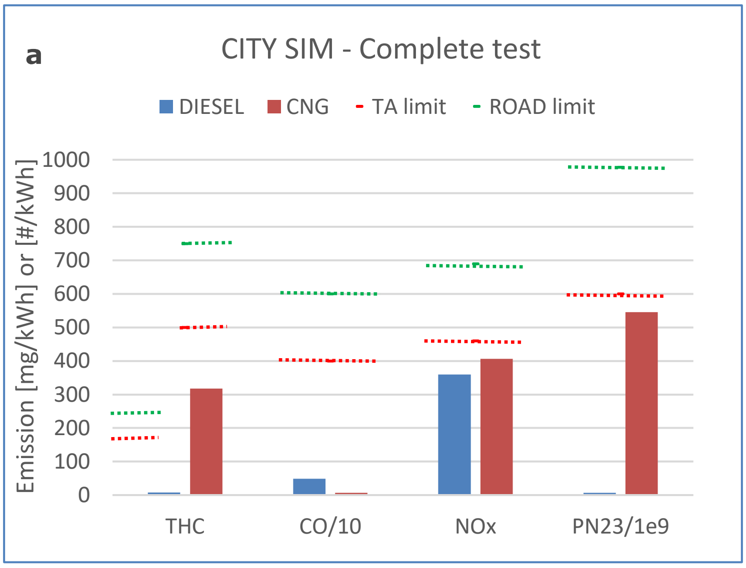
Figure 26. Emission Factor in ISC_LIKE cycle (without exclusion). **a**: brake specific; **b**: distance specific.

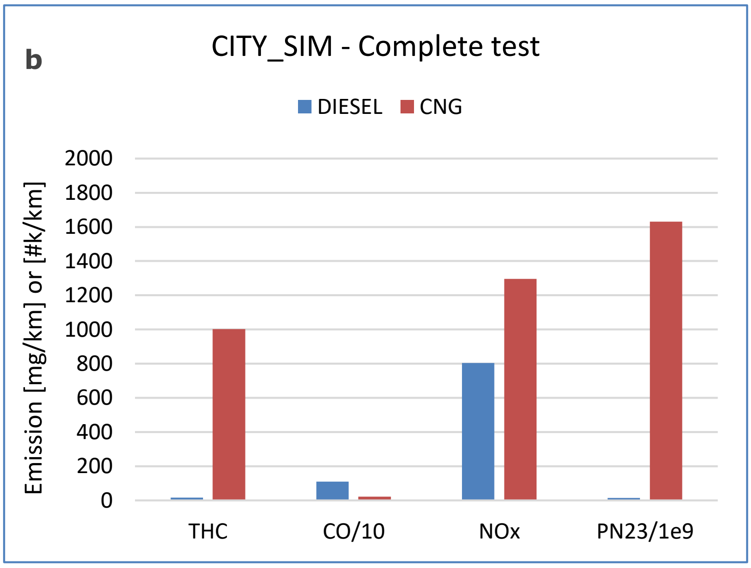




Source: JRC Vela, 2019

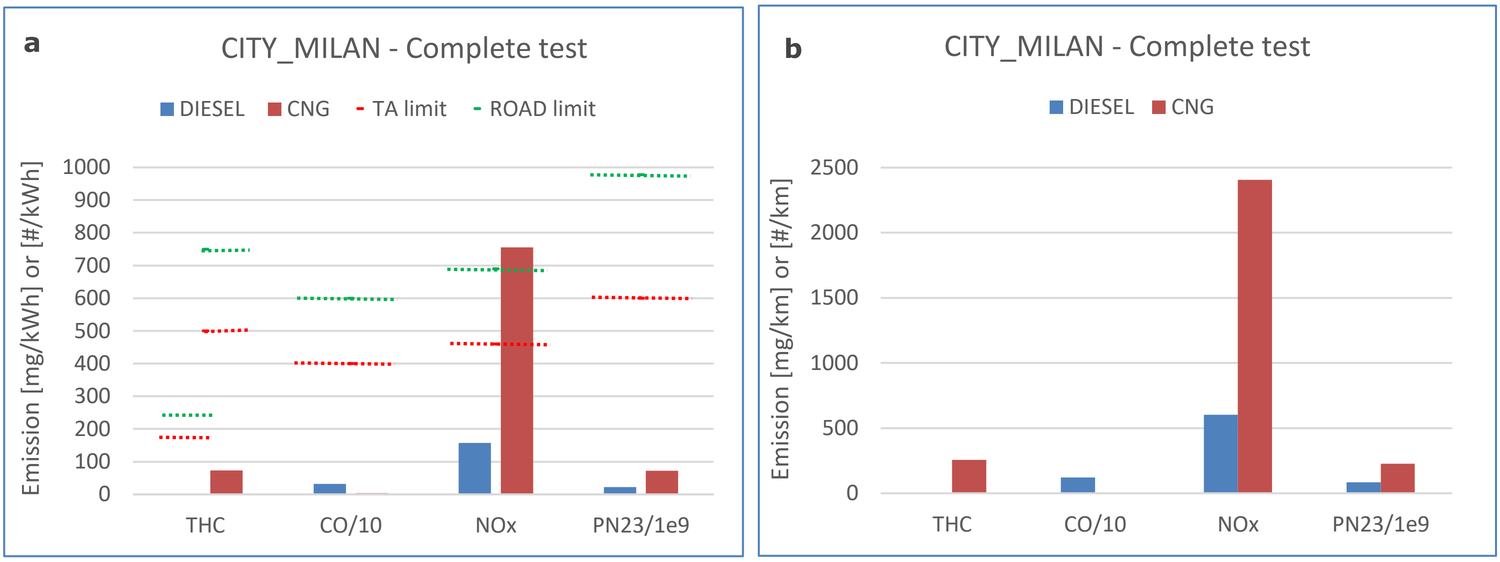
Figure 27. Emission Factor in CITY_SIM cycle (without exclusion). **a**: brake specific; **b**: distance specific.





Source: JRC Vela, 2019

Figure 28. Emission Factor in CITY_MILAN cycle (without exclusion). **a**: brake specific; **b**: distance specific.



Source: JRC Vela, 2019

Table 9 and **10** contain a summary of all emission factors, respectively on brake specific and distance specific basis. In these tables also the CO_2 has been reported for completeness. The quantities potentially over the regulated emission limits (TA limit) are highlighted in red (remember that a regulated limit not exist for these cycles).

Table 9. Brake Specific emission summary (averaged for all test repetition).

	Brake Specific Emission									
COMPLETE TEST	THC [mg/kWh]		CO [mg/kWh]		CO2 [g/kWh]		NOx [mg/kWh]		PN [#/kWh]	
	Diesel	CNG	Diesel	CNG	Diesel	CNG	Diesel	CNG	Diesel	CNG
ISC_LIKE	0.5	171.5	864.7	251.0	622.6	555.5	199.2	82.5	1.31E+10	7.73E+11
CITY_SIM	7.4	317.3	491.5	71.1	663.6	491.8	359.7	406.3	6.46E+9	5.45E+11
CITY_MILAN	0.8	73.5	320.3	40.9	612.6	813.7	157.1	755.3	2.23E+10	7.19E+10

Source: JRC Vela, 2019

Table 10. Distance Specific emission summary (averaged for all test repetition).

	Distance Specific Emission									
COMPLETE TEST	THC [mg/km]		CO [mg/km]		CO2 [g/km]		NOx [mg/km]		PN [#/km]	
	Diesel	CNG	Diesel	CNG	Diesel	CNG	Diesel	CNG	Diesel	CNG
ISC_LIKE	0.5	215.4	882.1	315.8	635.1	695.3	203.2	103.7	1.33E+10	9.78E+11
CITY_SIM	16.6	1001.9	1099.0	213.4	1483.8	1531.6	804.1	1296.0	1.44E+10	1.63E+12
CITY_MILAN	3.0	257.4	1216.5	53.5	2280.6	2711.3	602.6	2405.4	8.31E+10	2.26E+11

Source: JRC Vela, 2019

In the Diesel truck (assumed as reference), the regulated pollutant emissions measured during the ISC_LIKE test were 0.5 mg/kWh (0.5mg/km) for THC; 864.7 mg/kWh (882.4mg/km) for CO; 199.2 mg/kWh (203.2 mg/km) for NO_X; $1.31 \cdot 10^{10}$ #/kWh ($1.33 \cdot 10^{10}$ #/km) for PN. In addition, this vehicle registered a value for CO_2 of 622.6 g/kWh (635.1 g/km). On the other hand, for CNG vehicle the respective values were on average 171.5 mg/kWh (215.4

mg/km) for THC; 251.0 mg/kWh (315.8 mg/km) for CO; 82.5 mg/kWh (103.7 mg/km) for NO_X; $7.73*10^{11}$ #/kWh ($9.78*10^{11}$ #/km) for PN. Furthermore, the CO_2 emitted was equal to 555.5 g/kWh (695.3 g/km).

During the CITY_SIM cycle, the regulated pollutant emissions measured for the Diesel truck (reference) were 7.4 mg/kWh (16.6mg/km) for THC; 491.5 mg/kWh (1099.0 mg/km) for CO; 359.7 mg/kWh (804.1 mg/km) for NO_X; $6.46*10^{9}$ #/kWh ($1.44*10^{10}$ #/km) for PN. In addition, the CO_2 values was 663.6 g/kWh (1483.8 g/km). Considering the CNG vehicle, the respective values were on average 317.3 mg/kWh (1001.9 mg/km) for THC; 71.1 mg/kWh (213.4 mg/km) for CO; 406.3 mg/kWh (1296 mg/km) for NO_X; $5.45*10^{11}$ #/kWh ($1.63*10^{12}$ #/km) for PN. Moreover, this vehicle registered a value for CO_2 of 491.8 g/kWh (1531.6 g/km).

The most important test for our purpose, that was to evaluate the emission performances under realistic operating conditions, in order to support a fleet renewal initiative in the city of Milan, naturally was the CITY_MILAN cycle. In this cycle the Diesel vehicle emitted on average 0.8 mg/kWh (3.0 mg/km) for THC; 320.3 mg/kWh (1216.5 mg/km) for CO; 157.1 mg/kWh (602.6 mg/km) for NO_X; $2.23*10^{10}$ #/kWh ($8.31*10^{10}$ #/km) for PN. In addition, the CO_2 emitted was equal to 612.6 g/kWh (2280.6 g/km).

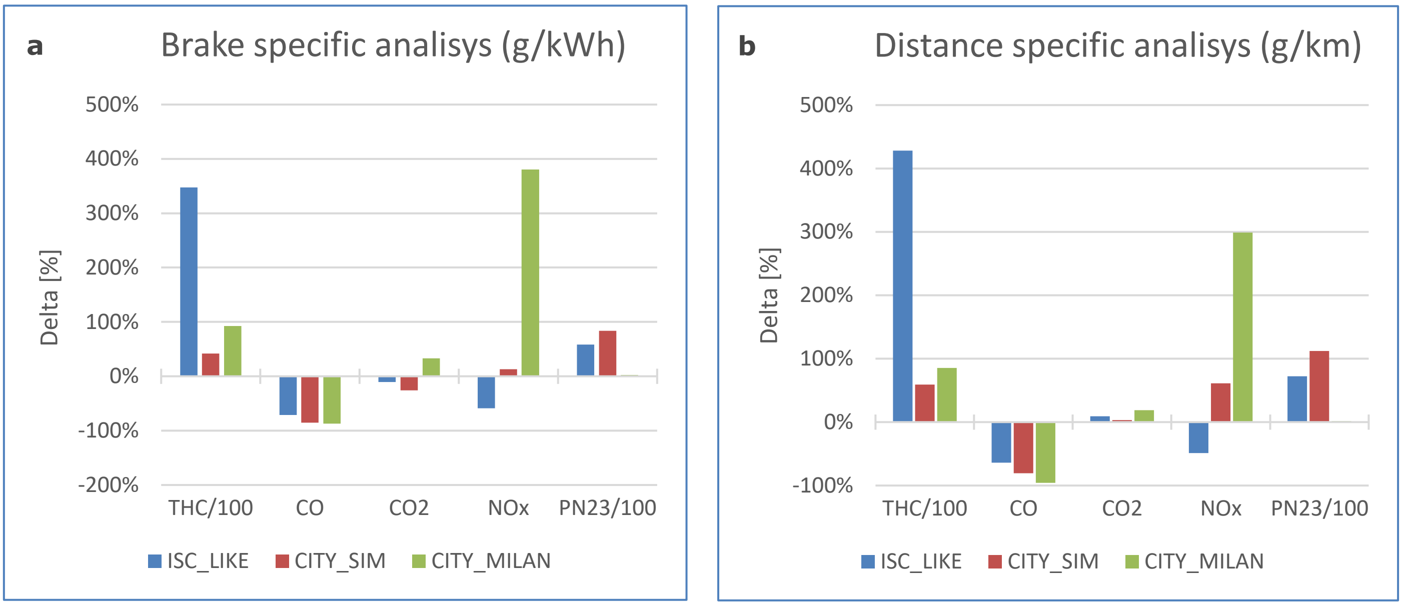
On the other hand, for CNG vehicle the respective values were on average 73.5 mg/kWh (257.4 mg/km) for THC; 40.9 mg/kWh (53.5 mg/km) for CO; 755.3 mg/kWh (2405.4 mg/km) for NO_X; $7.19*10^{10}$ #/kWh ($2.26*10^{11}$ #/km) for PN. The CO_2 values was 813.7 g/kWh (2711.3 g/km).

In conclusion, with reference to **Figure 29** and taking into account only the braking specific approach (in g/kWh or #/kWh), we registered a decreasing of CO (ISC_LIKE: -71%, CITY_SIM: -86%, CITY_MILAN: -87%) and a considerable increase in PN (ISC_LIKE: around 60 times; CITY_SIM: 84 times; CITY_MILAN: 2 times). It seems that also a large increase of THC is recorded. As already mentioned this is a little bit ambiguous, for diverse motives. In fact, it is important to highlight that the THC values for Diesel engine were very small and, for this reason, also a moderate increase in THC values for CNG truck translated into a considerable change of the percentage difference. On the other hand, it is worthy to remember that the HC limits is different between Diesel and CNG engines, since the contribute of Methane emission is quite important in the CNG trucks. In this differential percentage of variation (DELTA) between the two vehicles, the reference is the Diesel vehicles. A positive DELTA value means that the emission in the CNG truck were higher than in the Diesel one. On the other hand, a negative value means that the CNG truck had lower emission if compared to the Diesel vehicle.

Nevertheless, THC and CO were for both vehicles fulfilled the hypothetic limit (TA and ROAD limit) even when including cold start.

As NO_X trend was contradictory when comparing Diesel and CNG vehicles, it deserved a more careful analysis: only in ISC_LIKE cycle there was a decreasing of around -59%, while in the city conditions, namely CITY_SIM and CITY_MILAN cycles, we obtained respectively an increase equal to 13% and 381%. This fact is explainable with the large share of the motorway part, in which the higher exhaust temperatures permitted to the after-treatment systems in the CNG truck (TWC) to have excellent results in term of NO_X breakdown. Opposite results are found in the urban phases of all cycles, where the SCR can work with a lower temperature (<200°C) if compared with the TWC temperature (around 320/330°C). The temperatures considered were not a real light-off temperatures, in the traditional sense. In fact, they could be considered as the effective conversion temperatures, at which the NO_X reduction is practically complete. We called this temperature ECT. This temperature was higher than the respective light-off temperature, namely the temperature at which we achieved a reduction of 50% of the pollutant under investigation (normally indicated as $T_{[50]}$). Mainly, the SCR operating temperature is higher than the own ECT (as well as the light-off threshold) for more time in the whole “urban” cycles if compared with the TWC converter working temperatures. Another reason to be considered, it is the fact that the CNG vehicle mileage is lower than 3000km (not a de-greened engine - brand new), so we can only judge a non-completely stabilised engine and after-treatment devices and this may have an important impact in the final outcome.

Figure 29. Delta percentage analysis. **a**: Brake specific; **b**: Distance specific.

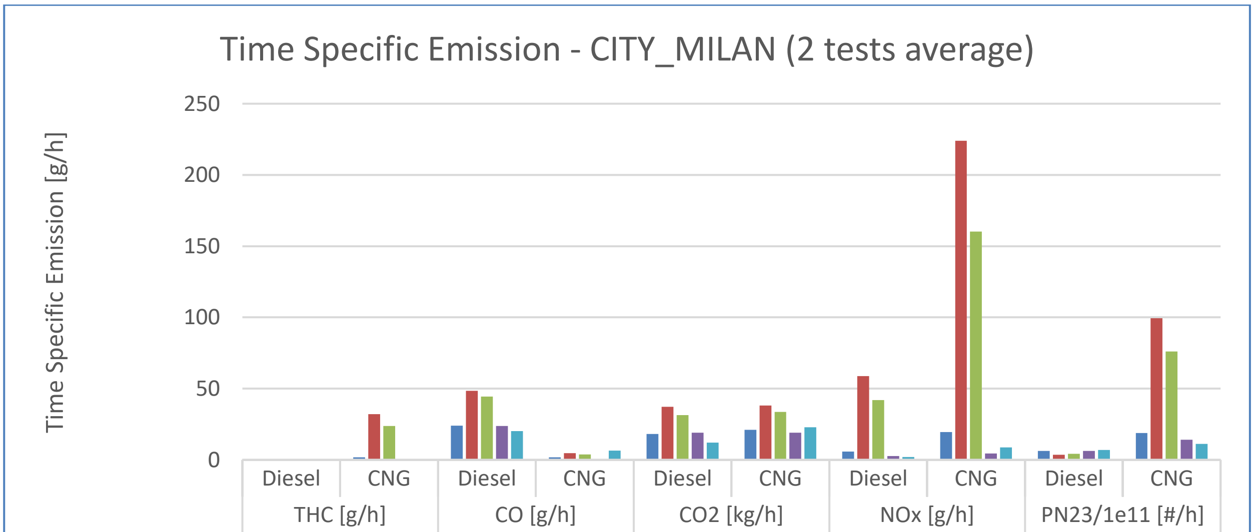


Source: JRC Vela, 2019

Another possible metric is to evaluate the emission factor based on operating time. These emission factors are obtained by dividing the integrated emission on hourly basis. **Figure 30** depicts the values of every regulated pollutant in the different parts of the CITY_MILAN cycle. The data are averaged on two tests cycle for every vehicle type. Also using the time specific emission metric referred to every hour of driving, at glance, it is clear that CNG vehicle presented higher NO_x and PN emission. Note that PN values have been divided by 10^{11}, to permit an overview of all the emissions factor in the same plot.

As usual, it essential to remark that this result is applicable only to the two vehicles under test, any other extrapolation could be misleading.

Figure 30. Time Specific Emission in CITY_MILAN cycle (average on 2 tests).



	THC [g/h]		CO [g/h]		CO2 [kg/h]		NOx [g/h]		PN23/1e11 [#/h]	
	Diesel	CNG	Diesel	CNG	Diesel	CNG	Diesel	CNG	Diesel	CNG
COMPLETE TEST	0.026551	1.700839	23.99283	1.852896	18.28729	21.07046	5.871875	19.43823	6.24E+00	1.89E+01
COLD START	0.442283	32.16748	48.45969	4.65946	37.34111	38.26058	58.89779	223.8906	3.50E+00	9.95E+01
APPROACH	0.309529	23.73058	44.44431	3.879612	31.52903	33.58061	41.87657	160.2965	4.21E+00	7.61E+01
COLLECTION	0.00055	0	23.86388	0.453929	19.00172	19.08423	2.720205	4.403768	6.37E+00	1.42E+01
RETURN	0	0	20.30612	6.507211	12.11877	23.01697	2.01946	8.669634	6.90E+00	1.11E+01

Source: JRC Vela, 2019

5.1.1 Mechanism that affected NO_X emissions level

All Euro VI diesel engines use either EGR combined with SCR or only SCR to reduce the engines NO_X emissions. An SCR catalyst needs to have a certain operating temperature before it can actively reduce NO_X using as reagent urea (the so-called AdBlue®). The catalyst heats up by the exhaust gas of the engine. A vehicle driving at a higher engine load has higher exhaust gas temperatures and can heat up a catalyst quicker and to a higher temperature. Vice versa, a diesel engine that is idling, has a low exhaust temperature (80-100 °C) which may cool down an SCR catalyst below the needed working temperature. This can also happen at low loads when driving. Depending on the type of catalyst, the catalyst temperatures need to be at least around 170-200 °C before it can reduce NO_X [**17**].

CNG Euro VI are principally equipped with a Three-way catalyst (TWC) mostly deriving for SI engines technology (Gasoline), in combination or not with a stoichiometric ratio. CO and NO_X have a lower light-off temperature (~ 250°C) than HC, mainly Methane (~ 450°C), therefore in cold condition catalyst starts to convert CO and NO_X first. This largely depends on the catalyst formulation as well as on the chemical structure of the fuel.

CH_4 is a very stable molecule and this justifies the high light-off temperature even if a dedicated catalyst Pd/Rh Al_3O_2-based is adopted. Sometimes a spark advance retarding in combination with a slight air/fuel ratio enrichment (higher stoichiometric value) could be used to light up the catalyst [**44**].

During CITY_MILAN cycles, both vehicles largely operated a low average speeds (around 7 km/h) due to its typical operation of refuse collection, in which the vehicle is stationary for a long time during loading, so the exhaust gas temperature had a lot of oscillation around the ECT threshold. The reason of the NO_X behaviour in our vehicles can be found in the performances of the catalyst converter because of the different ECT and light-off temperatures and the thermal inertia of the converters, mainly due to their different dimension, mass and materials composition as supports/substrates (e.g. wash-coated monolith) and catalysts.

Catalyst converter thermal inertia and light-off temperatures

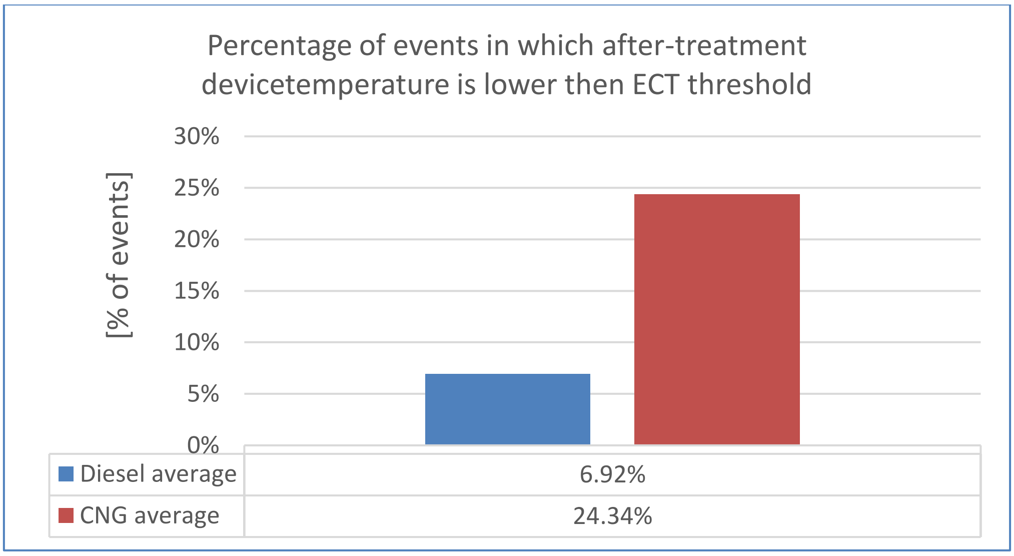
Catalysts have a thermal inertia which means that it takes time to warm up and it also takes time to cool down when the engine does not produce much exhaust heat, for instance when the vehicle is idling. How much NO_X is actually reduced at a certain moment therefore also depends on the previous history: what happened before that moment. In Diesel engines, for an effective SCR catalyst operation, it is beneficial that periods of low speed and low load be preceded by periods with higher speeds and loads. Frequent higher load operation may help to keep the SCR catalyst warm enough. Additionally, catalysts can buffer urea and NH_3. Urea which has been dosed to the catalyst at temperatures above about 200°C, can take care of NOx conversion in the temperature range of 150-200°C (even when there is no urea injection in this period). Some vehicles [**17**] clearly showed low average NO_X emissions due to intermittently driving low loads and speeds and higher loads and speeds. Such conditions occurred where a vehicle serviced a few streets in small neighbourhood of the city after which it drove via rural roads at higher speed and loads to another part of the city. On the other hand, the CNG TWC light-off temperature is higher for natural gas than in the corresponding gasoline engine (250/280°C) and the catalyst warmup period is longer for CNG [**44**, **45**]. On top of those two factors, Methane (CH_4, the main constituent of natural gas) has low chemical reactivity and so requires significantly higher activation energy [**46**] passing from a low temperature to another. Probably the CNG engine ran slightly rich, reaching the maximum of efficiency in a very narrow window with lambda values below 1. The conversion of NO_X in the TWC within this window is only partial, in the meantime the competition with CO and NO oxidation reactions put additional limitation to the successful abatement of NO_X (nitrogen oxide emission).

In the metropolitan cycle (CITY_MILAN), the Diesel engine SCR temperature was lower than 200°C only around 7% of the time. This percentage of events, in which the SCR temperature is below the ETC temperature (that we have estimated as a threshold equal to 200°C), is lower but close to what other researchers measured in USA (11%) for refuse trucks [**47**, **20**]. In our study, the SCR temperature (broadcasted by the ECU) was on average >200°C (approximately 245°C in CITY_MILAN COLLECTION part) probably because the hydraulic system that was used to take in and compress the garbage, increased the power demand and consequently kept the SCR catalyst temperature high even though the vehicle was idling around 60% of the time. However, this also means that other refuse vehicles without such system might not be able to exceed 200°C at the SCR catalyst, as it was the case for many vehicles in the literature studies, e.g. [**17**].

In the CNG engines, the TWC ECT and the light-off temperature is very sensible to the variation of air-fuel ratio caused for instance by a potential inadequate functioning of the auxiliaries (see next paragraph). In our CNG engine, there was not the possibility to broadcast the TWC temperature through the ECU, so we estimated it starting from the exhaust temperature profile. Under the previous hypothesis an effective conversion threshold temperature (ECT) could be hypothesized in the range 300-330°C [**48**], higher than the usual range for a SI engine. Furthermore, Rh in TWC has been well known for its important role in removing NO_X in the automotive engine exhaust. However, the Rh supported on Al_2O_3, commonly employed for the TWC system, is prone to catalyst deactivation caused by the high temperature exhaust stream, particularly under an oxidative environment [**49**]. In addition, the presence of oxygen in the feed has been examined and found to strongly alter the kinetic behaviour of noble metals according to the extent of the H_2/O_2 reaction which competes with the NO/H_2 reaction. On Pd/Al_2O_3, the predominant H_2/O_2 reaction depletes the surface hydrogen concentration inducing a dissociation step on a nearest-neighbour vacant site whereas hydrogen assists the dissociation of NO on Rh/Al_2O_3. Regarding $Pd\text{-}Rh/Al_2O_3$, competitive adsorptions would not likely occur with NO preferentially adsorbed on Rh. Such a result is supported by the weak partial pressure dependencies of the selectivity to N_2O formation similarly to Rh/Al_2O_3 which demonstrates that only Rh is involved in the formation of N_2 and N_2O on $Pd\text{-}Rh/Al_2O_3$. Nevertheless, it was found that Rh incorporation to Pd has a strong detrimental effect on the formation of nitrogen which suggests that TWC structure might alter the adsorptive properties of rhodium in interaction with palladium [**50**].

Figure 31 depicts the statistical percentage of events in which the after-treatment device (SCR and TWC) could not work properly, as the temperature of the device itself is under the light-off temperature (real in case of SCR and estimated in case of TWC. It is good to point out that between the Diesel truck tests performed in December 2018 and the CNG truck test on January 2019, there was a substantial difference in ambient temperature in average of 4°C. Also this circumstance was not beneficial for the CNG vehicle.

Figure 31. Statistical percentage of events in which the after treatment device could not work properly based on the number of events in which the after treatment device did not reach the light-off temperature.

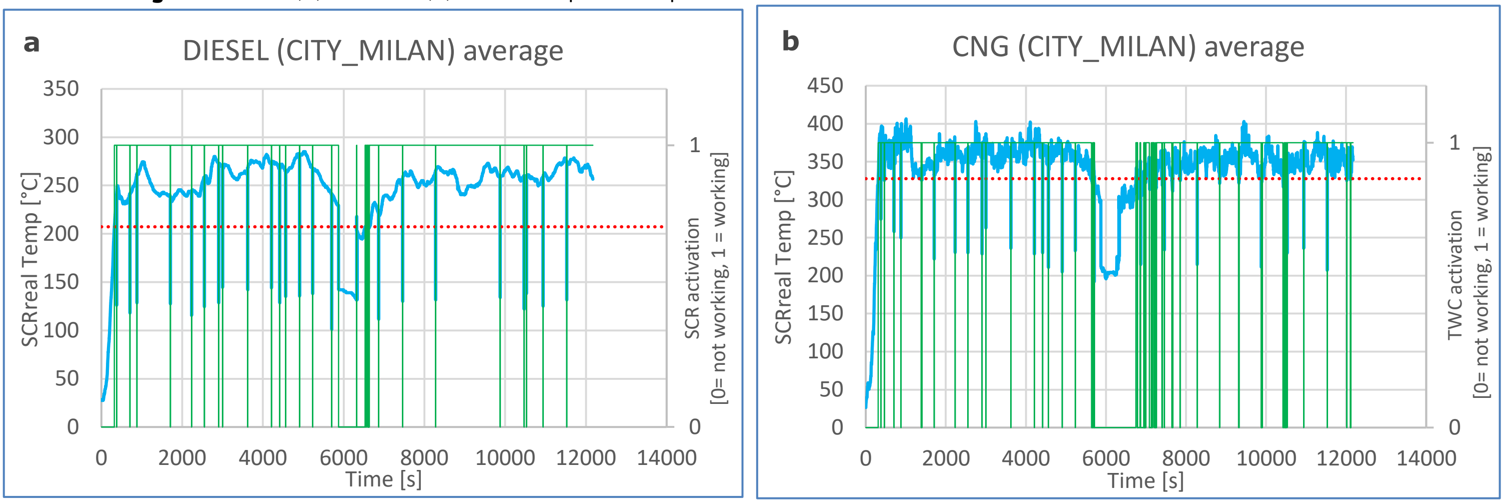


Source: JRC Vela, 2019

The statistic reported in **Figure 31**, shows a hypothetical scenery of the percentage of possible not efficient functioning of the after treatment based on the number of events in which the after-treatment device did not reach the ECT temperature. The temperature of the device (SCR for Diesel engine and TWC for CNG engine) gives only a statistic indication, in fact, in general, in some cases the device could work properly, even if its temperature is slightly below the ECT and light-off temperature, due to the thermal inertia of the converter, which means that it takes time to warm up, but, in the same way, it also takes time to cool down when the engine does not produce much exhaust heat, for instance when the vehicle is idling.

Figure 32 shows the relationship between the catalyst converter temperature (real for SCR and estimated for TWC) and its ECT threshold. On the right axis is possible to observe the status of the hypothetical device activation and the consequently reducing activity (0=not working; 1=working). These graphs are merely indicative and do not take into account the thermal inertia effects.

Figure 32. SCR (**a**) and TWC (**b**) device temperatures profile



compare with the ECT threshold.

Source: JRC Vela, 2019

Even though the gas exhaust temperatures were, as expected, absolutely notably higher in CNG than in Diesel vehicle, the higher percentage of events in CNG theoretically below the activation threshold (ECT temperature) confirmed that the impact of this factor together with a greater thermal inertia behaviour in CNG have an enormous impact on the NO_X reduction capacity of the TWC device.

Auxiliary power

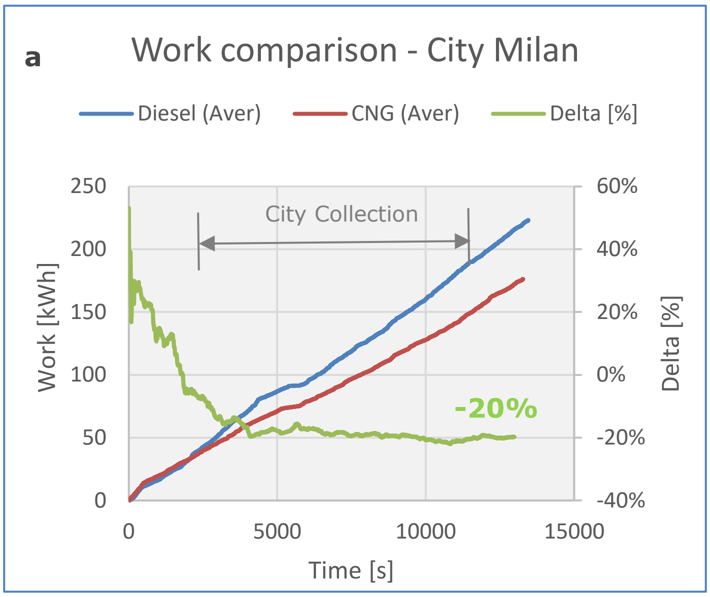
Generally speaking [**17**], refuse collection vehicles uses the power take-off (PTO) of the engine to drive a hydraulic system that is needed to operate the garbage press (about 4-10% of the maximum power). The auxiliary in the Diesel vehicle had an average higher percentage impact when compared to the CNG truck. Therefore, the Diesel engine exhaust temperature was then sufficiently higher, due to a relative high torque also at low engine speed. On Diesel case, as well as in CNG vehicles, the average vehicle speed of the operation was very slow, but for the Diesel a relative high power demanded from the PTO made that the engine ran at a sufficient high load on average to keep the SCR catalyst warm enough during long periods with many stops for garbage collection. The previous statement is supported by considering the operation in the municipality of Milan, where the CNG vehicle presented many engine shutdowns during the compacting activities when a certain amount of material was already introduced in the loader, meaning there is an increase of the resistance for the pumps. In this situation, the engine switched off many times due to a probably wrong setting of some parameters in the compaction unit control system.

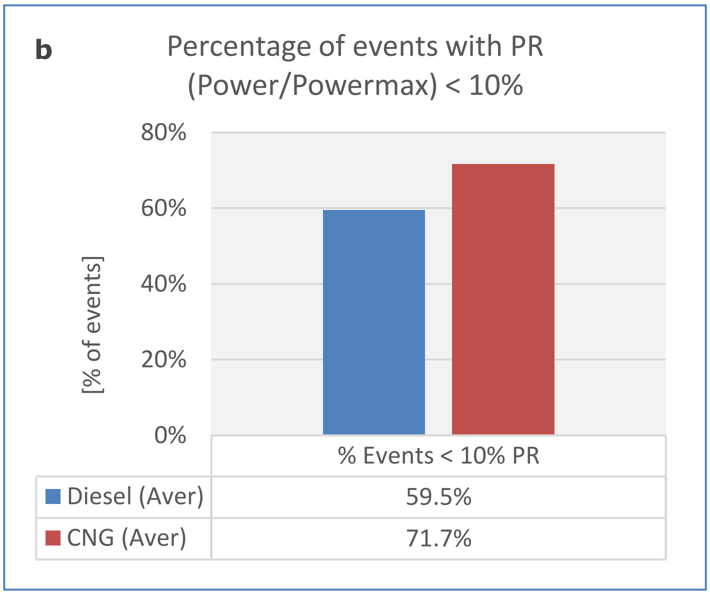
It is essential to notice that during the CITY_MILAN COLLECTION phase, the Work/Distance ratio W/D had an imbalance towards the Diesel truck (W/D_{Diesel}: 5.1 – W/D_{CNG}: 3.9). Assuming that the distance travelled was roughly the same (see **Table 4**), it is possible to explain this difference with a higher use of the PTO necessary to activate the hydraulic pumps, giving a relative higher load and thus also higher exhaust temperature [**20**]; while it is a little bit misleading in the other cases, in which the auxiliaries were not activated, or only partially as in the CITY_SIM cycle, where the activation of the hydraulic pumps was without any compacting activities. **Figure 33a** depicts a comparison between the total work cumulated during the CITY_MILAN cycle. The value was an average of two tests for every truck.

As clearly stated, the difference was significant: the total work done by the Diesel engine was on average 20% higher than the work done by the CNG vehicle. This was confirmed also by the number of events of the ratio

Power/Power$_{max}$ (PR number). The events with PR<10% is 59.5 and 71.7% respectively for the Diesel and the CNG vehicles (see **Figure 33b** for reference).

Figure 33. a: Work comparison Diesel vs CHG vehicle; **b**: Percentage of events < 10% of PW/PW$_{max.}$





Source: JRC Vela, 2019

On top of the previous discussion, the comparison between the fuels reveals that the main source of NO_X emissions is cold start, as highlighted in the dedicated session (see paragraph **5.2.3**). As already declared, the cold-start phase, lasting on average around 600/700 seconds, was responsible for both vehicles more than 60% (Diesel: 79.6%, CNG: 63.8%) of the NO_X emissions of the entire metropolitan route (CITY_MILAN). This means that the COLLECTION phase was more significant in CNG truck, in fact in this phase we registered a percentage increase of NO_X equal to 53.8% if compared with the Diesel vehicle. In CNG, the NO_X peak is most likely higher and the duration of elevated emissions is slightly longer, due to two aspects: methane (the main constituent of natural gas) has low chemical reactivity and so requires significantly higher activation energy [**46**], and on the other hand the catalyst warmup period is longer than expected in CNG. Probably the CNG engine ran slightly rich, reaching the maximum of efficiency in a very narrow window with lambda values below 1. The conversion of NO_X in the TWC within this window is only partial, in the meantime the competition with CO and NO oxidation reactions put additional limitation to the successful abatement of NOx (nitrogen oxide emission) [**44**, **45**]. However, even after the full warmup of the engine and the after-treatment system, CNG exhibited higher levels of NO_X emissions, as well as some spikes. This is a consequence of the combined effect of engine-out emissions and the performance of the TWC using methane fuel in CNG mode.

Mainly the contribution of cold-start period as well as after-treatment device not perfect fully stabilized due to the poor mileage of the CNG vehicle (less than 3000km – CNG vehicle was brand new) played a decisive role in the observation of higher NO_X emission in CNG rather than in Diesel engine.

Figure 34 and **35** showed that in the cold start phase, Diesel after-treatment device (mainly SCR) started earlier to work if compared to CNG TWC. The integrated amount of NO_X emission (g) in the first 900s is around 2 times (+90.2%) higher in CNG as compared to the Diesel vehicle (**Figure 34a** vs **Figure 35a**). In plotting the parameters, only one test for every vehicle has been considered. The result is only qualitative, but still reliable. In the **Figures 34a** and **35a** the integrated NO_X in grams are plotted together with the temperature profile of the after-treatment device (SCR and TWC), respectively for Diesel and CNG vehicles. In correspondence to the flattening of the NOx integrated curve, it is possible to find the Effective Conversion Temperature (ECT) for the reducing device in use. This point represents the moment when the reduction of NO_X became high and almost complete. The ECT threshold is given by the intersection of the dotted blue line (point of NO_X effective conversion) together with the device temperature profile (green line). It is important to highlight that while the SCR temperature is measured, the TWC temperature profile is estimated starting from the exhaust temperature profile measured at the EFM. In **Figure 34b** and **35b** depict the NO_X mass emissions in relation with the intervention of the respective after-treatment device. On the right axis it is possible to observe the status of the hypothetical device activation and the consequently reducing activity (0=not working; 1=working) on the base of the ECT temperatures.

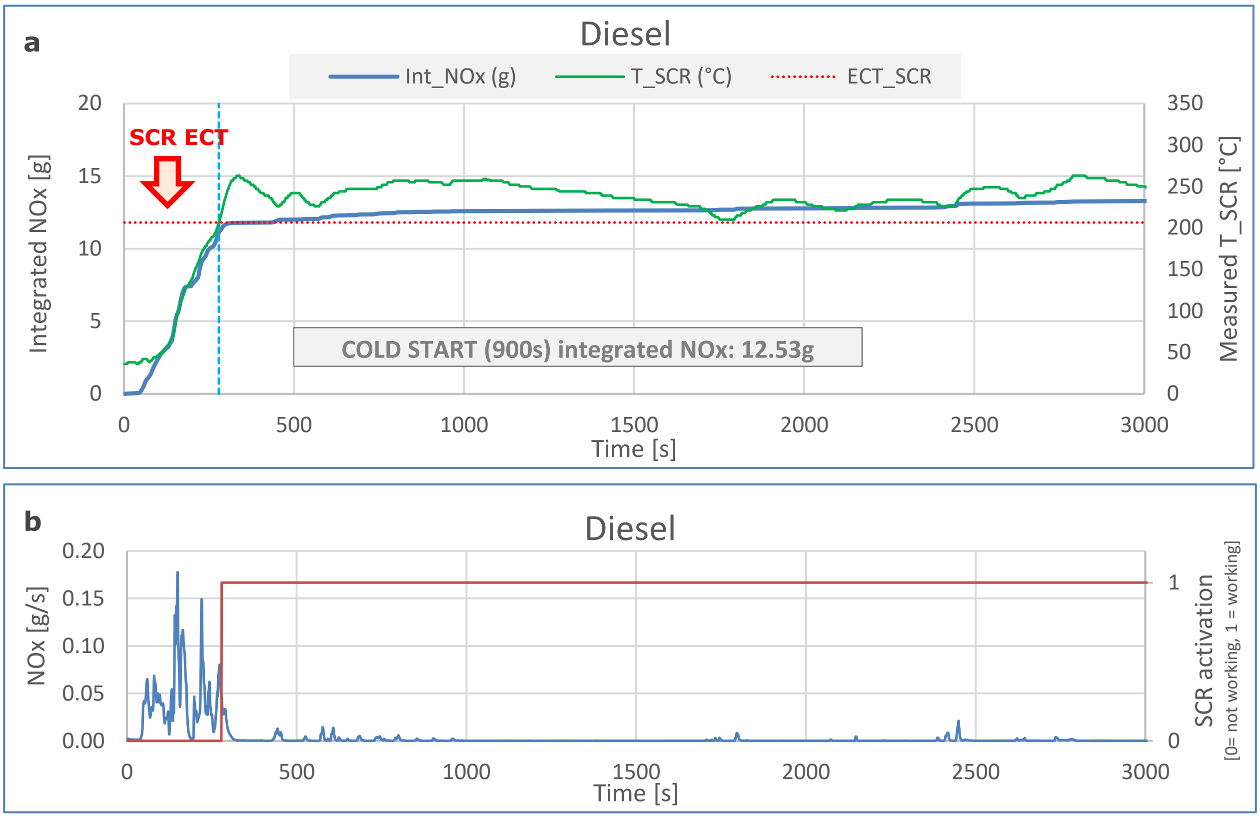
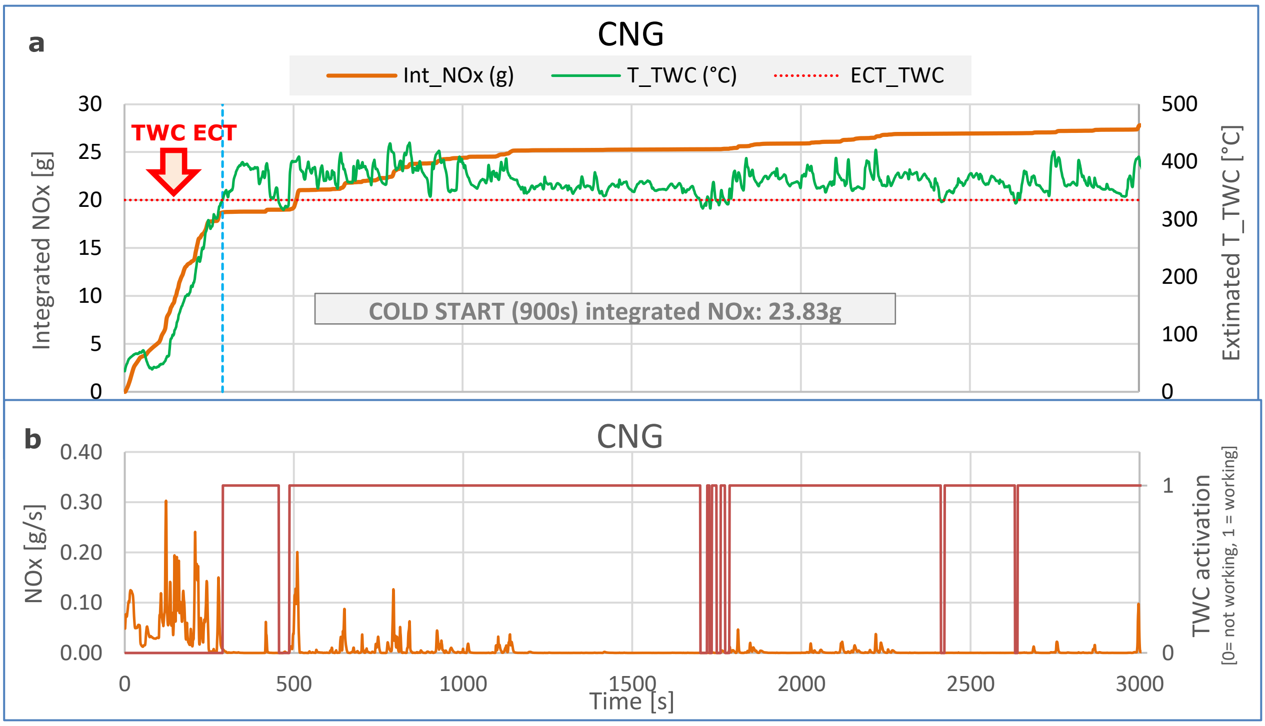


Figure 34. Diesel engine NO_x emission (**a**) and integrated emission (**b**) in cold start during CITY_MILAN cycle.

Source: JRC Vela, 2019

Figure 35. CNG engine NO_x emission (**a**) and integrated emission (**b**) in cold start during CITY_MILAN cycle.



Source: JRC Vela, 2019

5.2 Detailed results – Pollutants analysis

It was possible to determine the emission factors for hazardous pollutants of exhaust gases for both trucks at every cycle stage thanks to the typology of the cycles which gave a good repeatability. Hence, correlations were developed characterising the impact of dynamic properties of refuse collection on the emission of harmful compounds. Dynamic properties of vehicles were included indirectly, using the entire velocity range in urban traffic for a 2-D matrix of intensity of emissions of respective pollutants. Those figures were averaged within velocity ranges (Urban, Rural and Motorway bins). In addition, for every test pattern, also the cold start in the complete cycle has been considered, whilst the total IDLE has been introduced only for CITY_SIM and CITY_MILAN cycles.

In the following section, every single regulated pollutant (THC, CO, NO_X and PN) will be analysed and compared to highlight the difference between the Diesel and the CNG vehicle. Furthermore, a CO2 comparison and the ammonia assessment (only in laboratory tests) is also presented. In particular, the behaviour of every pollutant will be weighted in regarding to the cycle type and to the cycle phase. All the pollutant levels are presented using two metrics:

1) Brake specific emission in mg/kWh (THC, CO, NO_X), in g/kWh (CO_2) and in #/kWh (PN)

2) Distance specific emission in mg/km (THC, CO, NO_X), in g/km (CO_2) and in #/km (PN)

Furthermore, as already introduced at the beginning of this chapter, two limits are introduced where applicable:

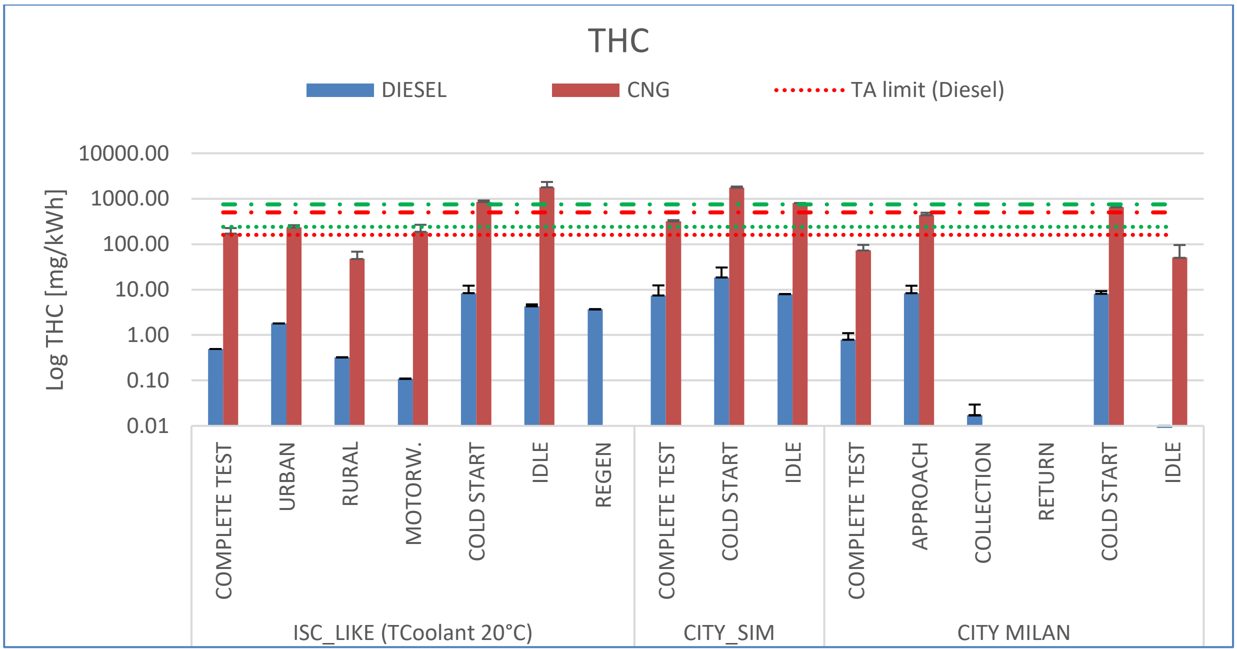
a) TA limit: it is the threshold applied to the engine at the dyno during the homologation test.

b) TA road: it is a sort of equivalent limit for the vehicle tested on road, considering a multiplication factor of 1.5 and of 1.63 time the TA limit, respectively for gaseous pollutants and PN.

All pollutant emissions reported averaged values based on at least two repetitions. In order to highlight the differences, the logarithmic representation has been used. As the outcomes of the complete test has already been analysed and discussed in the previous session, in the following paragraph, we will try to enter into detail of the partial results, in particular giving emphasis and taking care of the URBAN behaviour of the two vehicles under comparison. A deep analysis is provided for different phase of the CITY_MILAN cycles. Obviously the idling values for distance specific emission make no sense and it has not been reported.

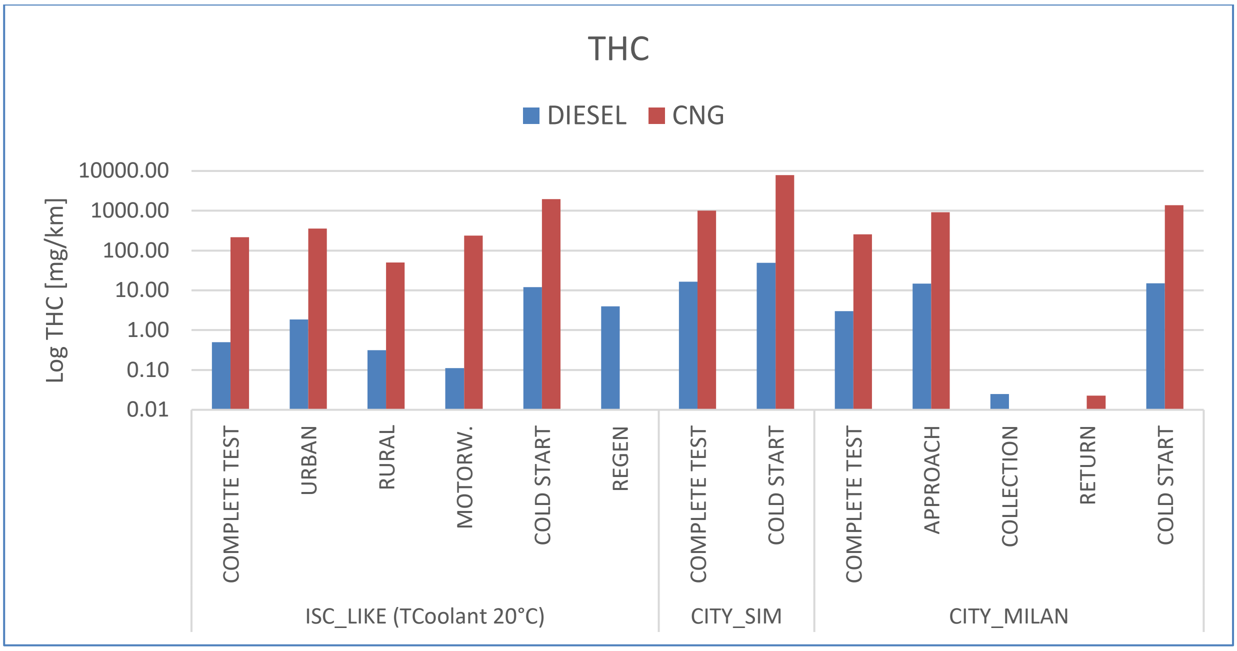
5.2.1 THC (Total Hydrocarbons)

Figure 36. THC emission in mg/kWh (braking specific emission) – Expressed in logarithmic notation.



Source: JRC Vela, 2019

Figure 37. THC emission in mg/km (distance specific emission) – Expressed in logarithmic notation.



Source: JRC Vela, 2019

Due to a problem in the Non Methane Flame Ionization Detector (NMFID) analyzer, it was not possible to measure or calculate the Methane (CH_4) and non-methane fraction of the Hydrocarbons, so even for CNG truck the Hydrocarbons are reported as Total Hydrocarbons (THC), without any distinction. The HC composition in CNG vehicle is mostly composed by methane compounds, for this reason only the relative limit (0.5 g/kWh) has been used also for the total Hydrocarbons without committing a large error if the NMHC has not been considered and subtracted. In fact, the indicative limits proposed as TA limit and ROAD limit refer to the THC limits, even if the homologation test of CNG Euro VI engines at dyno test bench, includes two different partial limits, one for NMHC (0.16 g/kWh) and one for CH_4 (0.5 g/kWh). See **Annex 1** for reference. When comparing methane emissions from CNG and diesel engines, it is clear that the CNG engines emitted much more due to the fact that the fuel practically comprise only compressed CH_4.

The highest THC emissions of both vehicles (see **Figure 36** and **37**) were observed under cold start and low speed conditions, where mostly refuse vehicles usually operate. Under these conditions the catalyst temperature of the engine is lower than the light-off threshold, thus affecting negatively its efficiency.

Analyzing the ISC_LIKE cycle, in Diesel truck, THC emissions ranged from 0.11 mg/kWh – 0.11 mg/km (ISC_LIKE - Motorway) to 1.80 mg/kWh – 1.87 mg/km (ISC_LIKE - Urban), which were significantly lower to those found for the CNG truck. In fact, in the latter, the THC emissions ranged from 187.71 mg/kWh – 239.47 mg/km (ISC_LIKE - Motorway) to 233.90 mg/kWh – 355.96 mg/km (ISC_LIKE - Urban).

In the cold start (CS) and in engine idling (Idle), with reference only the braking specific emission, the CNG vehicle presented values higher respectively of two and three order of magnitude as compared to the diesel vehicle ($Diesel_{CS}$: 8.35 g/kWh vs CNG_{cs}: 845.8 g/kWh and $Diesel_{Idle}$: 4.28 g/kWh vs CNG_{Idle}: 1787 g/kW). IDLE in ISC could be misleading because it represented only 3% in time and normally was during starting operations.

The situation was more or less similar in the CITY_MILAN cycle. During the approach part, Diesel vehicle THC emissions were considerably lower if compared to the CNG ones. Diesel: 8.34 g/kWh vs CNG: 437.15. Also in this test, cold Start and Idle followed the same trend of the ISC_LIKE. $Diesel_{CS}$: 8.08 g/kWh vs CNG_{cs}: 654.1 g/kWh and $Diesel_{Idle}$: 0.01 g/kWh vs CNG_{Idle}: 51.05 g/kW). Here the percentage of idling is substantial around 60% and 67% for Diesel and for CNG truck respectively.

THC distance specific emissions followed the same trend as braking specific emissions. Similar results have been reported elsewhere [**51**] and are lower compared to those reported in the literature for CNG HDV [**15-17**]. Similar THC emissions have been reported for CNG buses tested over different conditions [**52**, **53**].

5.2.2 CO (Carbon Monoxide)

CO emissions were significantly higher in the Diesel vehicle as compared to the GNC one. Anyway total CO emissions of both vehicles were below the Type Approval Euro VI emission standard (4.0 g/kWh or otherwise 4000 mg/ kWh) under all testing conditions, independently from the speed and operating mode.

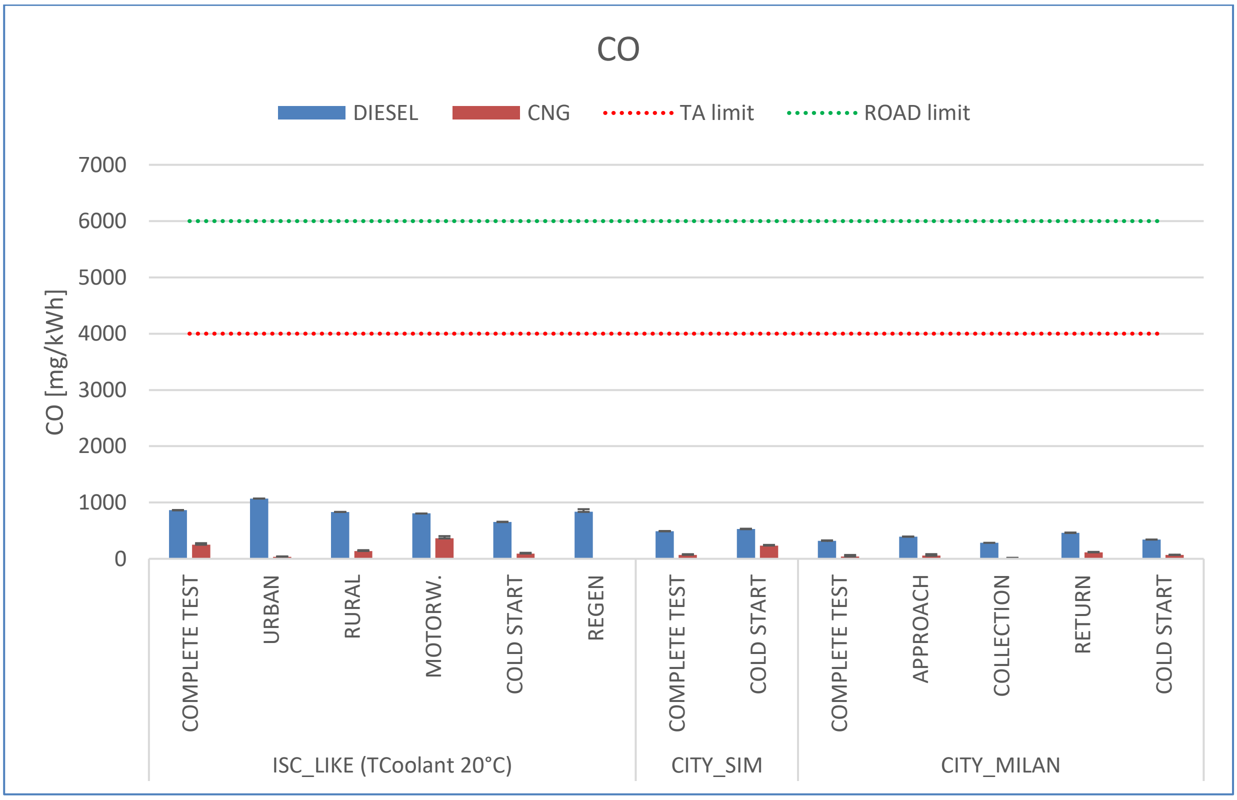
As expected, in the CNG engine lower CO emissions (see **Figure 38** and **39**) were registered at lower speeds parts of the tracks, in which normally they were operating with low and medium loads. In general, this is the common situation where mostly refuse collection trucks work. In these conditions, characterized by heavier accelerations, this effect was amplified owing to the presence of a probable leaner combustion, which resulted in more oxygen available in the combustion chamber to oxidize CO, as a result of a not perfect control of the air-fuel (A/F) ratio. While in Diesel engine the CO emissions were more stable and flat in every phases, with a slight increase in the urban parts.

Analysing the ISC_LIKE cycle, in Diesel truck, CO emissions ranged from 805.4 mg/kWh – 829.2 mg/km (ISC_LIKE - Motorway) to 1071.11 mg/kWh – 1111.42 mg/km (ISC_LIKE - Urban), which were significantly higher to those registered for the CNG truck, where they ranged from 35.73 mg/kWh – 46.76 mg/km (ISC_LIKE - Urban) to 363.41 mg/kWh – 461.00 mg/km (ISC_LIKE - Motorway).

The situation is similar in the CITY_MILAN cycle, in which the percentage reduction between the two vehicles is pronounced in high speed part (RETURN). $\text{Diesel}_{\text{return}}$: 463.18 mg/kWh vs $\text{CNG}_{\text{return}}$: 115.95 mg/kWh).

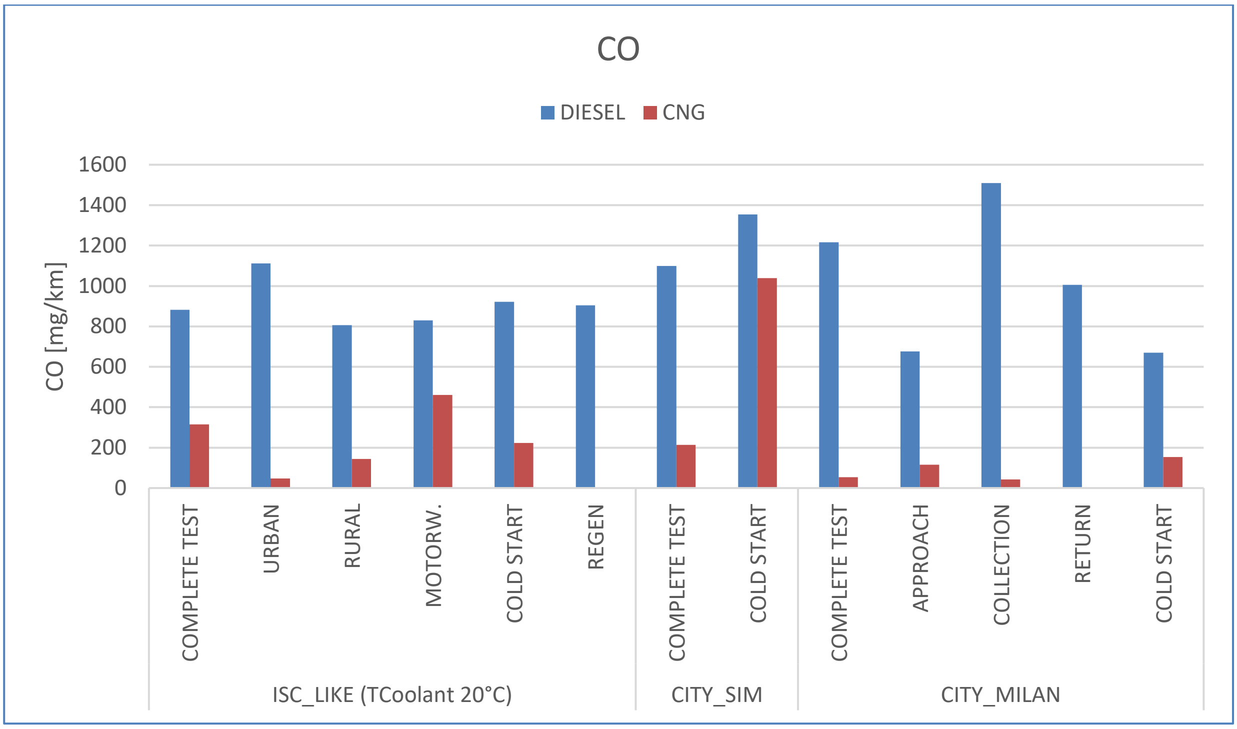
It is worthy to comment that in COLLECTION phase there is a considerable reduction of the emission in favour of the CNG truck ($\text{Diesel}_{\text{collection}}$: 285.35 mg/kWh vs $\text{CNG}_{\text{collection}}$: 11.36 mg/kW).

Figure 38. CO emission in mg/kWh (braking specific emission).



Source: JRC Vela, 2019

Figure 39. CO emission in mg/km (distance specific emission).



Source: JRC Vela, 2019

5.2.3 NO_X (Nitrogen Oxides)

NO_X emissions of both trucks were below the Euro VI emission standard (see TA limit) under ISC_LIKE and CITY_SIM complete test. Diesel vehicle remained below the limit threshold also in CITY_MILAN complete cycle, while the CNG vehicle was above it.

In general, for both trucks, some exceedances were observed with low speed conditions, in particular during cold start phase (**Figure 40** and **41**). The cold start and the period just after it were relevant for emissions. The reason is that usually a cold engine produces higher emissions, while the emission control system is not yet at operating temperature and thus does not effectively reduce those emissions. High NO_X values in low speed stages were due to the mix of high engine out NO_X emissions and their ineffective catalytic reduction. In fact, in our investigation, cold start and some city conditions (e.g. traffic/congestion) resulted in high engine out emissions [**38**] and low exhaust gas temperature and consequently the after-treatment systems could not work properly. On average, the contribution of the cold start to the NO_X emissions was 79.6% and 63.8% in the CITY_MILAN cycle and 29.6% and 46.4% in the ISC_LIKE cycle, for Diesel and CNG vehicles respectively.

NO_X emissions of the Diesel vehicle over the ISC_LIKE test varied from 186.83 mg/kWh – 192.36 mg/km (Motorway) to 313.00 mg/kWh – 324.78 mg/km (Urban), while CNG ranged from 16.20 mg/kWh – 20.72 mg/km (Motorway) to 295.17 mg/kWh – 444.17 mg/km (Urban). In general, the CNG truck behaved better under ISC_LIKE tests, while it behaved worst in CITY_MILAN cycle. **Table 11** gives an overview of the partial results in all the cycle parts in brake Specific Emissions in mg/kWh for the CITY_MILAN cycle.

Table 11. NO_X braking specific emissions in CITY_MILAN divided into the different phases of the cycle.

	Brake Specific Emission [mg/kWh]					
CITY_MILAN	Complete	Approach	Collection	Return	Cold Start	Idle

Diesel	157.1	1095.4	65.1	9.87	1232.8	87.3
CNG	755.3	2970.9	100.1	326.5	4687.4	450.7

Source: JRC Vela, 2019

In the low speed phases over the cold start (mainly COLLECTION and some parts of RETURN), NO_X emissions for the diesel vehicle were almost one order of magnitude lower than the previous technology. This thanks to a significant improvement with the introduction of optimized SCR also at lower temperature.

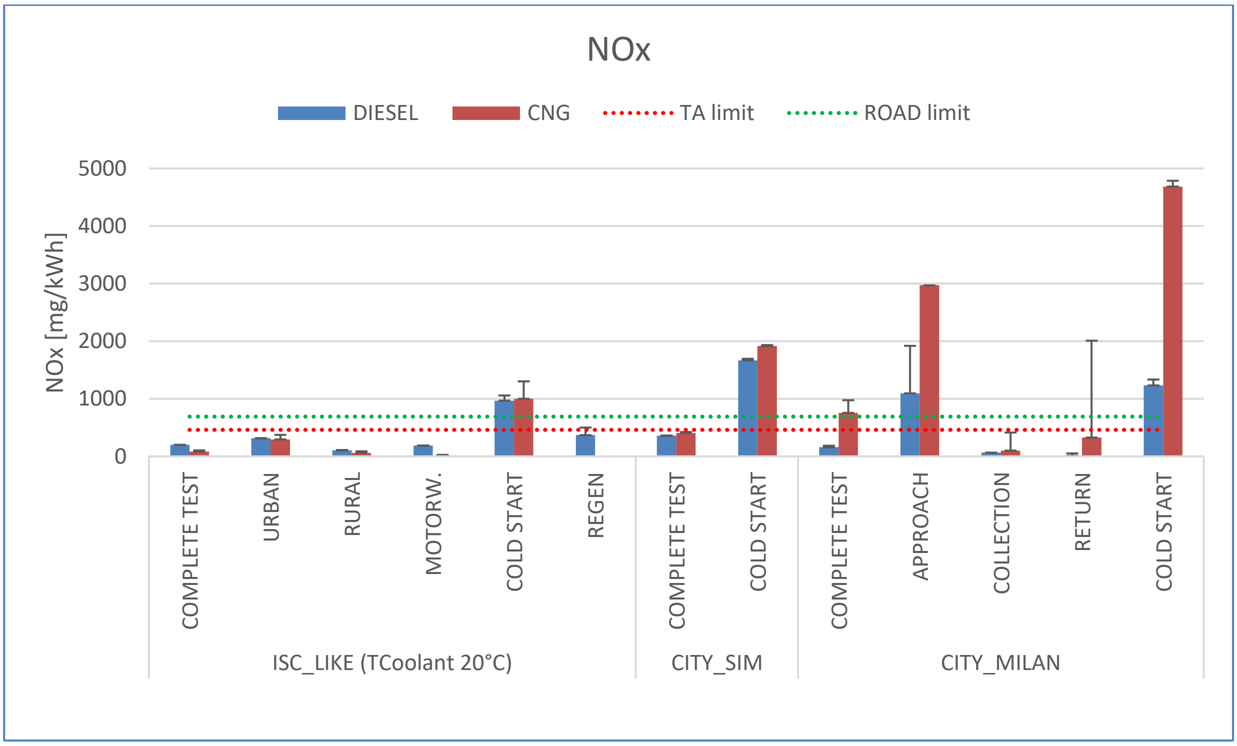
The better Diesel outcome in the CITY_MILAN tests in which low speeds and low exhaust temperatures were observed, could be ascribable to the SCR being able to work with a lower temperature (>200°C) if compared with the TWC ECT temperature (estimated around 330°C). Mainly, the SCR temperature was higher than the own ECT threshold for more time in the whole "Urban" cycles if compared with the working TWC converter temperatures. The differences in ECT threshold and a certain higher thermal inertia of the SCR compared to TWC [**44**] add some support our findings (see **Figure 31**, **32**, **34** and **35** for more details). Another important point is the evaluation of the Work/Distance (W/D) ratio as introduced in paragraph **5.1.1**. As already mentioned, in the CITY_MILAN cycle, the Diesel engine SCR temperature was lower than 200°C only 7% of the time, probably because the hydraulic system which move the pumps, increased the power demand and consequently kept the SCR catalyst temperature high even though the vehicle was idling around 60% of the time.

On the other hand, in the CNG truck, the TWC ECT temperature, as well as the light-off one, was very sensible to the variation of air-fuel ratio caused by a potential inadequate functioning of the auxiliaries.

As already discuss in **Paragraph 5.1.1,** the contribution of cold-start period was determining in the overall results. CNG showed NO_X emission nearly 4 times higher than the Diesel. In both vehicles the cold part lasted on average 600/700s and was also included in the respective approach phases.

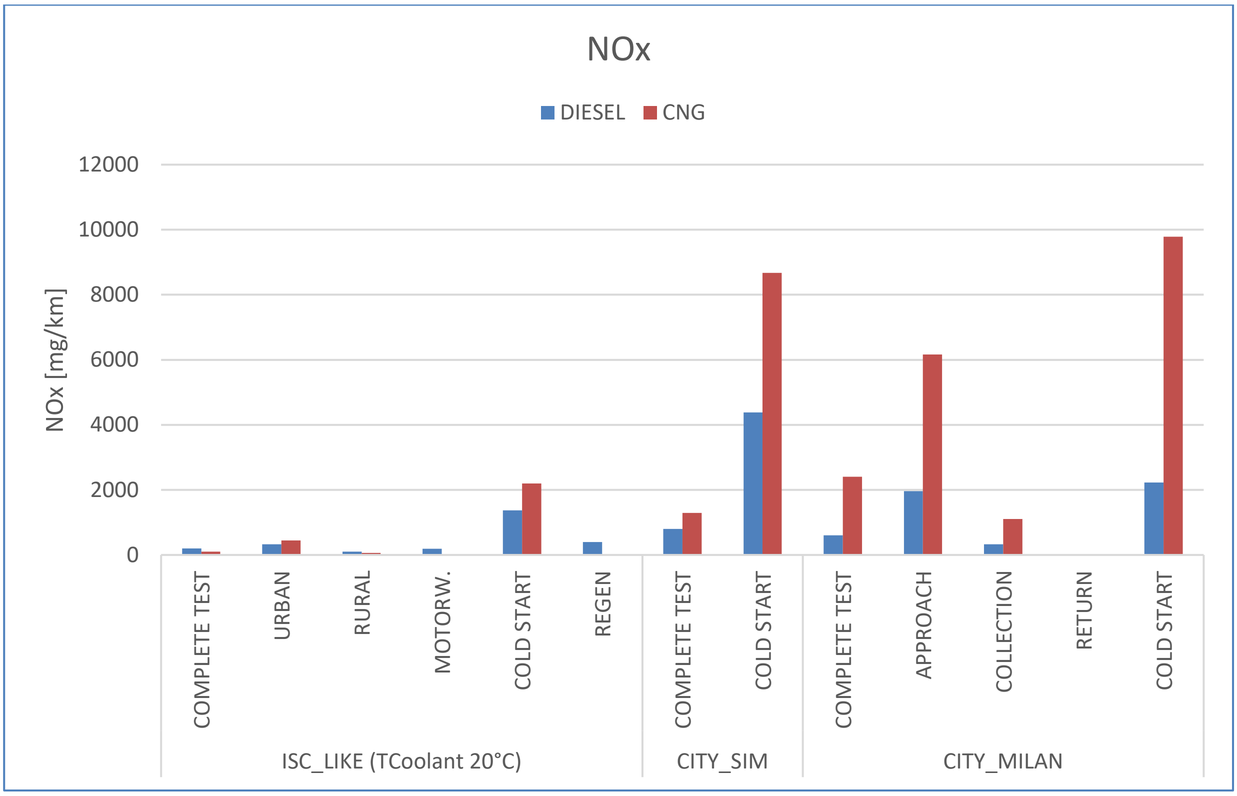
Furthermore, a supplementary reason to be considered, it is the fact that the CNG vehicle mileage is lower than 3000km (the truck was brand new), so we can consider the engine and the after-treatment devices (TWC) not perfect fully stabilized and this may give a very important impact in the final outcome. All the general considerations introduced in the presentation of the overall results (**Paragraph 5.1.1**), are still valid also for the single test phases.

Figure 40. NO_X emission in mg/kWh (braking specific emission)



Source: JRC Vela, 2019

Figure 41. NO_X emission in mg/km (distance specific emission).



Source: JRC Vela, 2019

Table 12 refers to the NO_X emission level of different Diesel refuse collection vehicles over the real world operation in different period, that is for different model years and different regulations in chronological order.

Table 12. NO_X emissions of Diesel refuse collection vehicles over actual operation cycles.

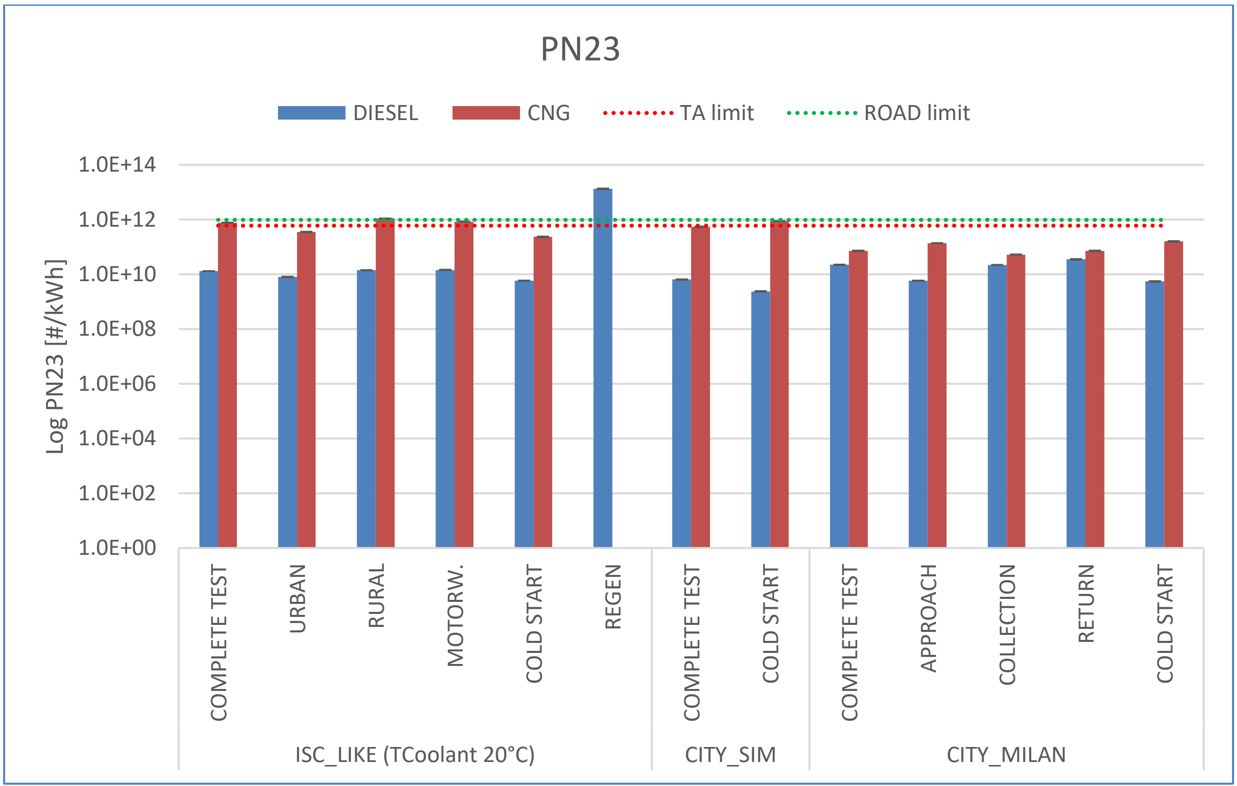
Emissions level	No. vehicles	NO_X [g/km]	Mean speed [km/h]	Reference
MY 2002-2006	3	35-62 [1]	16-25 [2]	[11]
MY 2005-2007	4	27-32	20-27	[12]
MY 2012 [3]	2	2.6-5	22-27	[12]
Euro IV	1	18-25	n/a	[13]
Euro V	1	32	6-8	[5]
Euro VI	8	0.4-10.2	6-27	[14]
Euro VI [3]	1	0.7	8-9	**This study**

[1] Estimated from distance percentages and emissions per mile from each part of the cycle. [2] Estimated from time percentages and average speed from each part of the cycle. [3] with SCR. MY=Model Year.

Source: JRC Vela, 2019

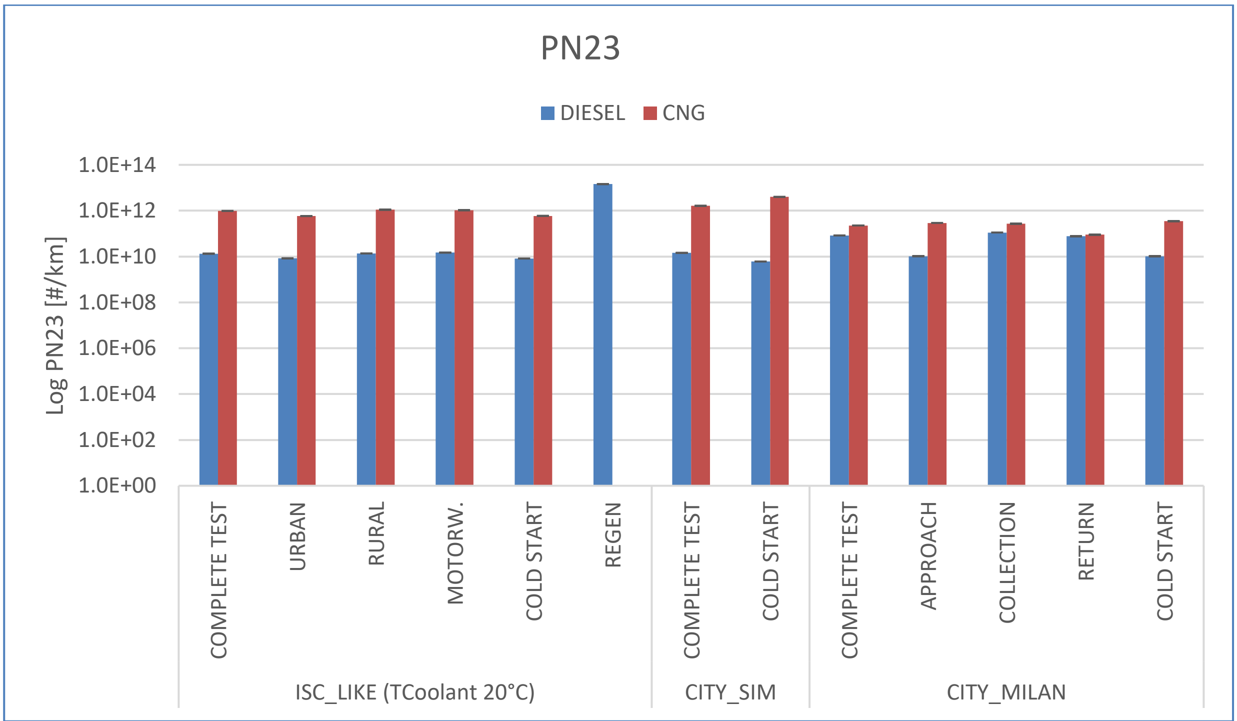
5.2.4 PN (Particle Number)

Figure 42. PN emission in #/kWh (braking specific emission) – Expressed in logarithmic notation.



Source: JRC Vela, 2019

Figure 43. PN emission in #/kWh (braking specific emission) – Expressed in logarithmic notation.



Source: JRC Vela, 2019

PN emission levels of Diesel vehicle appear to be not of concern due to the effectiveness of the currently available DPF systems. Calculated emission factors were at least one order of magnitude lower than the current laboratory type approval limit (TA) and appear to be at the lower limit of the range given in the literature for older technology HDVs featuring a DPF system. For PN an additional factor (ROAD limit) of 1.63 is foreseen.

Figure 42 depicts that PN did not show high oscillation in ISC_LIKE cycle for the Diesel vehicle. This exhibited averaged PN emissions of 8.02×10^{9} (URBAN), 1.41×10^{10} (RURAL) and 1.44×10^{10} (MOTORWAY) particles/kWh, in accordance to what has been published in the literature for Euro VI HDVs [**30**]. These values are within one and two order of magnitude lower if compared with the respective phases of the CNG truck: 3.53×10^{11} (URBAN), 1.09×10^{12} (RURAL) and 8.43×10^{11} (MOTORWAY) particles/kWh. In the ISC_LIKE complete cycle, the CNG vehicles slight exceeded the TA limit, as well in CITY_SIM tests. Same trend has been reported in the distance specific metric (see **Figure 43**).

Analysing the CITY_MILAN cycle and its breakdown in different classes speed, it is obvious that all the differences between the two means were imputable mainly to the cold start (Diesel: 5.50×10^{9} versus CNG: 1.60×10^{10} particles/kWh), in fact the same difference was found also in the APPROACH phase, while the COLLECTION and RETURN steps were about the same magnitude, 2.20×10^{10} and 3.52×10^{10} particles/kWh for Diesel vehicles and 5.27×10^{10} and 7.17×10^{10} particles/kWh for CNG truck respectively.

Overall PN emissions demonstrate a better effectiveness of Diesel engine's DPF in abating particle emissions, however PN emissions as well as differences among speed phases are very low, therefore not permit to draw solid conclusions. According to literature, Diesel PN emissions of the same level have been reported for other Euro VI HDV tested on-road [**9**] [**37**]. PN levels of the current study on Diesel truck were at the lower limit of the range given in the literature for older technology HDVs featuring a DPF system (5×10^{10}–2×10^{12} particles/km) [**54**].

5.2.5 CO_2 (Carbon Dioxide)

Despite not regulated, CO_2 is the most widely Greenhouse Gas (GHG) and its emissions along with those of CH_4 cause great concern for environmental as well as for economic reasons.

According to our investigation, if we consider the complete cycles, the overall CO2 emissions have an ambiguous trend and varied substantially: in CNG vehicle were on average lower than in Diesel truck for both braking specific and distance specific approach (see **Figure 44** and **45**) for ISC_LIKE and CITY_SIM tests, while they were diametrical opposite considering the CITY_MILAN route.

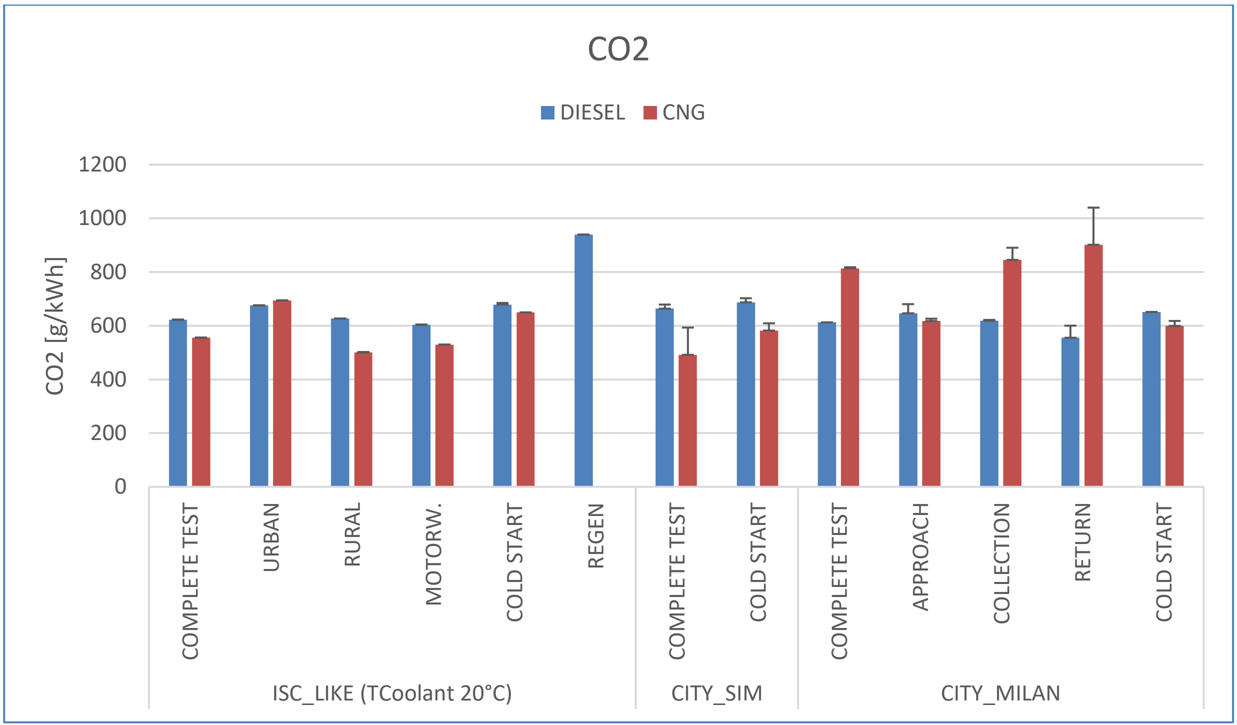
In particular, for complete test cycles, it was possible to observe a decreasing of -11% in ISC_LIKE, -26% in CITY_SIM and an increasing of around +33% in CITY_MILAN cycles (see **Table 9**). These data, as usual, used the Diesel vehicle as reference.

The reason is to be found in the difference of operation at low speed (in the so called "URBAN" part), as well as in the percentage weight of this part on the total cycle.

Analysing the CO_2 values broken down into speed bins and considering only the urban phases, for braking specific metric, they ranged from 618.58 g/kWh (CITY_MILAN - COLLECTION) to 675.88 g/kWh (ISC_LIKE – URBAN) for Diesel vehicle and from 694.39 g/kWh (ISC_LIKE – URBAN) to 845.35 g/kWh (CITY_MILAN - COLLECTION) for CNG vehicle. While in Diesel vehicle the variation in urban routes, between different cycles, seemed to be not very significant, in the CNG they had a big impact.

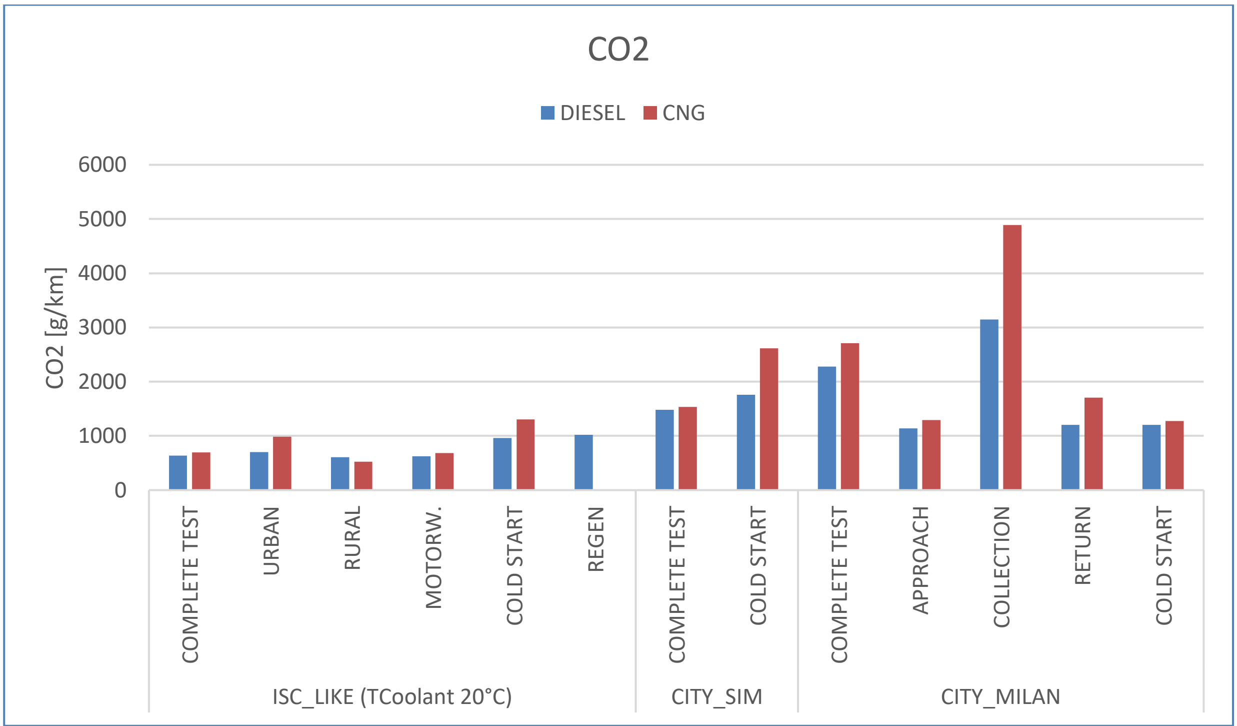
In ISC_LIKE and CITY_SIM test, no compaction activity was requested. Instead, during the COLLECTION phase of CITY_MILAN cycles, the total payload of the vehicles increased progressively with the amount of garbage collected. The difference in the CO_2 values can be attributed to the higher effort increasingly required to the CNG hydraulic pumps rather than to the Diesel ones to compress against the moving wall the quantity of waste gradually introduced into the container. More garbage is introduced more high is the resistance for the accessories. While in the ISC_LIKE and in the CITY_SIM complete cycle the CNG, as expected, presented a good saving in CO_2 emissions (respectively -10.8% and -25.9%), in the complete CITY_CYCLE the situation was opposite: the CNG vehicle emitted +35.7% of CO_2 if compared with the Diesel truck. This is an indirect validation of the hypothesis of a non-optimal setting of the hydraulic pumps that moved the accessories in the CNG vehicle. In fact, while in the DIESEL truck the CO_2 was on the same level if we compare the urban part of ISC_LIKE and the COLLECTION - a sort of urban for city cycle in Milan- in the same comparison, it is possible to observe a decisive CO_2 increase in the CNG truck (approximately +22% if compared with other 'Urban" routes where no real compacting operations were requested), in opposition to what is found in the CNG literature [**18**, **53**].

Figure 44. CO_2 emission in g/kWh (braking specific emission).



Source: JRC Vela, 2019

Figure 45. CO_2 emission in g/km (distance specific emission).



Source: JRC Vela, 2019

5.2.6 Other pollutants

Different exhaust after-treatment systems have been implemented over the years to control the emissions of criteria pollutants. However, while reducing the emissions of the target compounds these systems can lead to the emissions of other pollutants and/or greenhouse gases such as NH_3 or N_2O.

NH_3 (a precursor of fine particle formation in the atmosphere) and N_2O (a powerful greenhouse gas and the single most important ozone-depleting substance) are present in HDV exhaust due the use of urea/SCR DeNOx systems (i.e., NO_X reduction systems) [**55**].

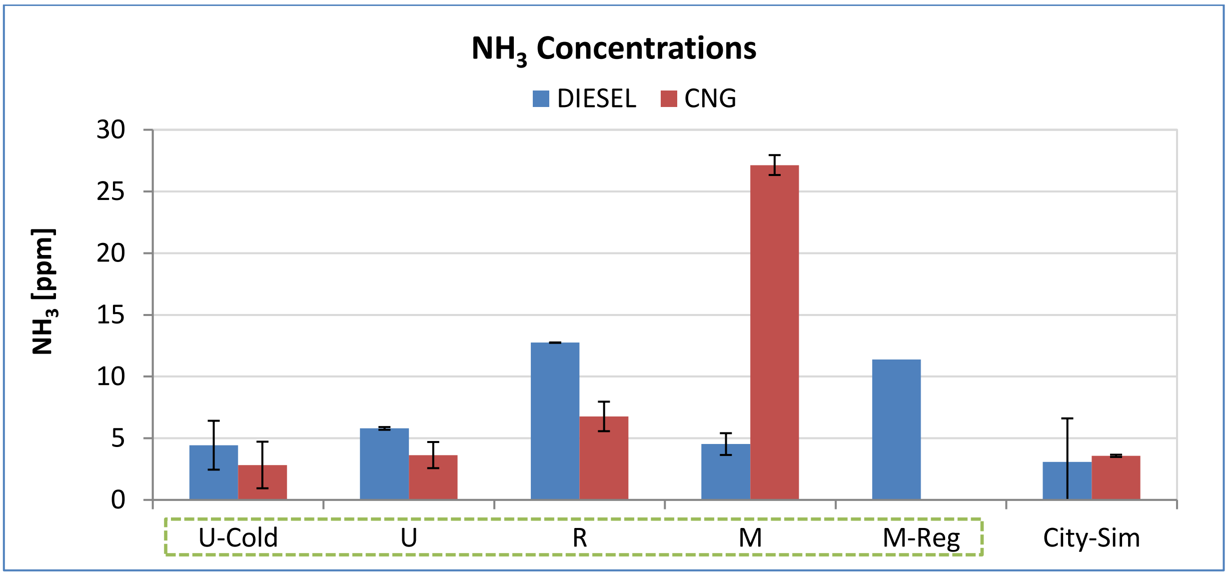
NH_3 emissions from vehicles are only regulated in EU and Korea, N_2O emission standards have recently been introduced by the U.S. Environmental Protection Agency (EPA) under the Clean Air Act [**56**]

NH_3 (Ammonia)

The road transport sector is considered not only one of the major contributor to PM and NO_X pollution in the European cities, where population densities are higher (80% of the European population are city denizen) as well as an important source of NH_3 [**57**].

The Euro VI standards also set emission limits for ammonia (NH_3) since the tighter NO_X standard will require the use of Selective Catalytic Reduction after-treatment (applicable only to Diesel), which in turn relies on the injection of urea into the exhaust stream. During the process, Ammonia can be produced as an unwanted by-product, due to the slippage of Ammonia in the SCR, hence the limits on Ammonia emissions for heavy-duty diesel (CI) vehicles (gasoline vehicles, also called “positive ignition” vehicles, are still exempt from the Ammonia limit). In the present on road experimental campaign the measurement of ammonia has been performed using the Smart Emissions Measurement Systems (SEMS). A dedicated report will address the results obtained with this pretty new technology and it will not be included in this document. Nevertheless, a laboratory measurement using FTIR equipment will be presented, just to have a measure of the amount of NH_3 emitted by the Diesel and CNG Refuse Collection vehicles [**20**].

Figure 46. NH_3 concentrations as measured with the FTIR in the laboratory.



Source: JRC Vela, 2019 [**20**]

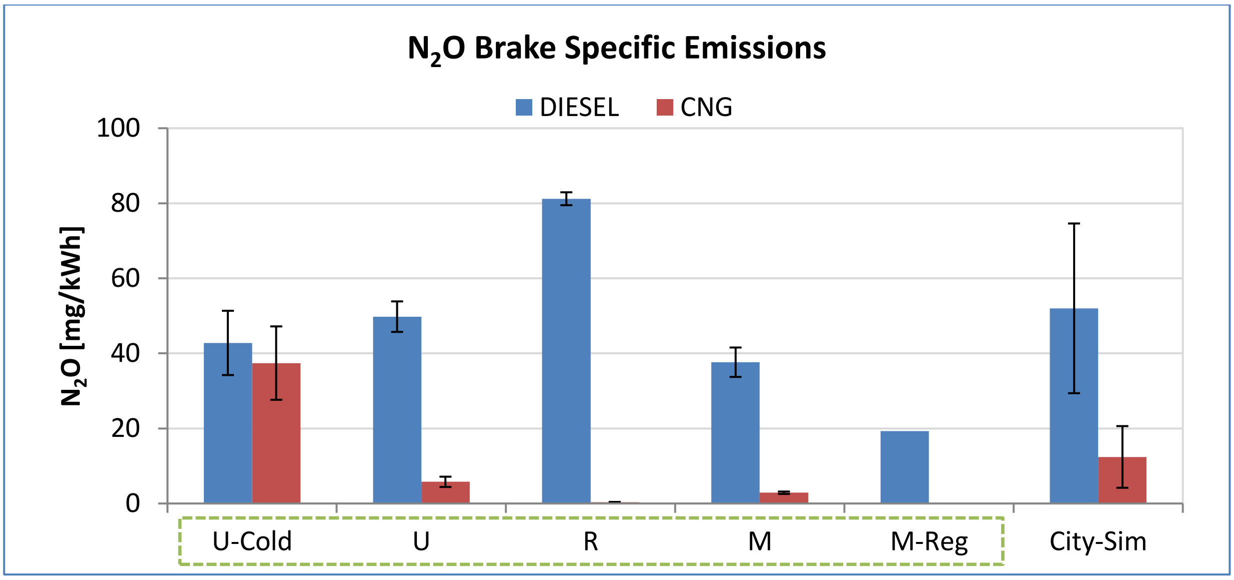
The FTIR measurements of NH_3 in the laboratory are summarized in **Figure 46**, error bars show max-min values of 2 repetitions. The NH_3 concentrations were low reaching 12 ppm in the rural and motorway part during regeneration. The mean cycle NH_3 concentrations were approximately 6 ppm, well within the 10 ppm limit for Euro VI heavy-duty engines. CNG engine exceeded the 10 ppm threshold, with an average of 15 ppm on the complete ISC_LIKE cycle, represented by the weight average of the different cycle phases: Urban (U), Rural (R) and Motorway (M). While in the CITY_SIM test the values are more or less the same. No other tests have been performed in the laboratory. It has to be mentioned that this pollutant presents a limit only for CI engines.

N_2O (Nitrous oxide)

Nitrous oxide (N2O) has potential dangerous effects even higher than CO_2 in a ratio of 200:1. Assessment of the impact of vehicle emissions on the global environment requires accurate data concerning nitrous oxide, N_2O, emissions.

Figure 47 depicts the N_2O brake specific emission measured in laboratory using a FTIR equipment. The values are an average of 2 test repetitions and the error bars show the minimum and maximum deviation from the average values. The N_2O emission factors are on average higher for Diesel vehicle than for CNG ones. The N_2O Diesel vehicle emission varied from 19.3 mg/kWh (in the REGENERATION part of the ISC_LIKE) to 81.2 mg/kWh (RURAL session of ISC_LIKE, with values higher than the Cold Start). CNG ranged from 0.34 mg/kWh (RURAL) to 37.41 mg/kWh at the cold start. The overall results were substantial lower in the CNG truck than the Diesel one.

Figure 47. N_2O brake specific emission measured with the FTIR in the laboratory.



Source: JRC Vela, 2019 [**40**]

5.3 ISC_LIKE vs ISC_COMPLIANT

In our study, we have used an In-Service Conformity cycle (called ISC_LIKE) that is not really fulfilling all the legislative prescriptions in terms of time sharing for the speed classes (Urban, Rural, Motorway). Our aim in introducing such a cycle was to have a higher weight of the “Urban” part to get closer to what happens in a real cycle in the city. Another reason to have introduced an ISC cycle is to compare our investigation to studies found in literature and to analyse the distance between the actual regulation cycle, designed for long haulage trucks, and the real driving condition in cities.

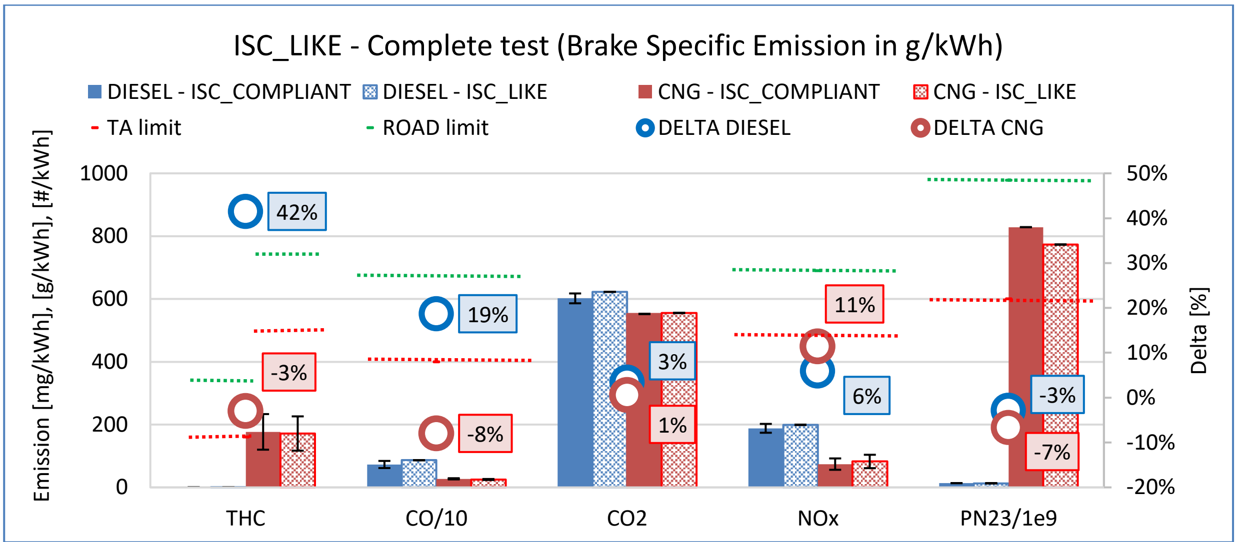
In this section a comparison between the ISC_LIKE and a ISC that fulfil all the requirements in the construction of trip composition is presented. **Table 13** shows the main trip composition (averaged on three tests) statistics between the different ISC cycles considered for both tests vehicles (Diesel and CNG). As clearly stated, the ISC_COMPLIANT fully satisfy the Regulation(EU)582/2011 [**7**] requirements regarding the percentage time shares of the ISC trip. Logically the values highlighted in green are compliant. An indication of the average speeds in every speed class has been added. In both approaches the COLD_START was considered and add to the overall results, even if in Euro VI step C is not foreseen. We chose to included it as it was an important part in the CITY cycle and we preferred to consider its impact also in the In-Service Conformity cycles.

Table 13. Statistic of trip composition for In-Service Conformity Cycles (ISC_LIKE vs ISC_COMPLIANT).

Speed Classification	Range	Trip Composition Requirements	ISC_LIKE Time Share [%]		ISC_LIKE Average Speed [km/h]		ISC_COMPLIANT Time Share [%]		ISC_COMPLIANT Average Speed [km/h]	
			Diesel	CNG	Diesel	CNG	Diesel	CNG	Diesel	CNG
Urban [U]	< 50 km/h	15-25%	38.0	36.5	32.1	28.9	21.4	24.0	31.8	28.5
Rural [R]	50-70 km/h	20-30%	19.3	21.4	65.2	64.1	23.1	24.8	64.9	63.3
Motorway [M]	>70 km/h	50-60%	42.7	42	88.3	88.4	55.5	51.2	88.6	85.9

Source: JRC Vela, 2019

Figure 48. In-Service Conformity comparison between ISC_LIKE and ISC_COMPLIANT.



Source: JRC Vela, 2019

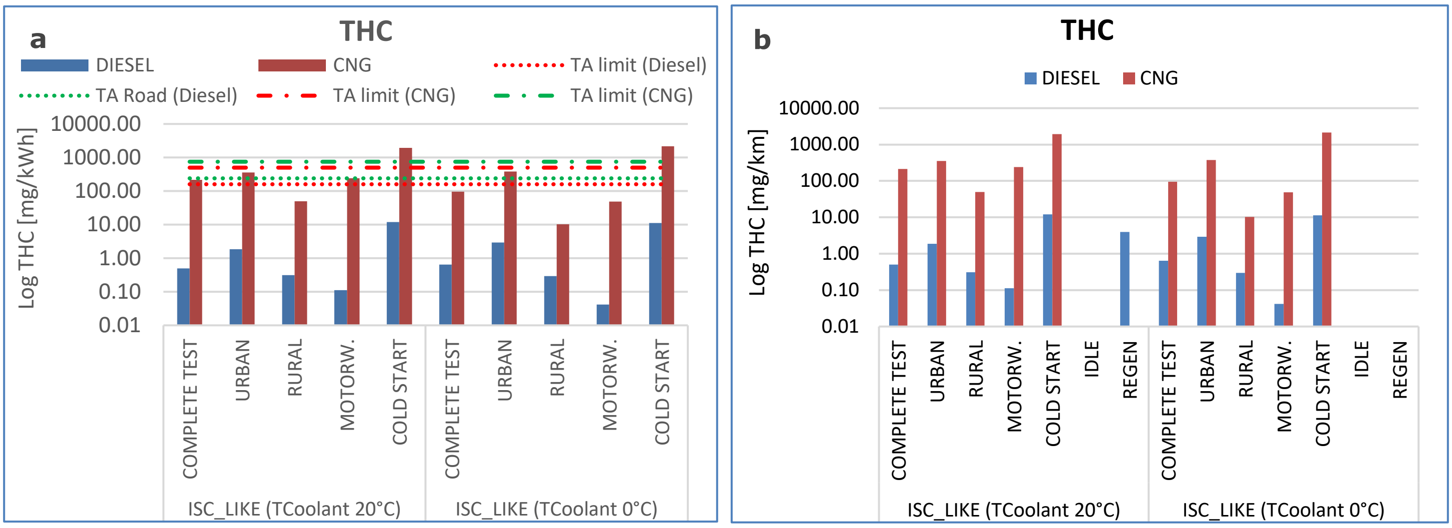
Figure 48 depicts the main variation passing from a ISC_COMPLIANT cycle to the ISC_LIKE. The percentage deviations between the two procedures are within a reasonable difference. In all cases the ISC_COMPLIANT is the reference cycle. In blue is represented the variation for Diesel truck and in red for the CNG one. The only THC in Diesel vehicle denotes a high impact: this is mainly due to the low values involved in THC emissions. Pay attention that the THC limits (TA and ROAD) are different for Diesel and CNG engine (see **Paragraph 5.2.1**).

5.4 Vehicles behaviour in ISC_LIKE test with different cold start temperatures

This section addresses the main difference in aggregate emission levels due to two diverse cold start temperatures. The emission pollutant analysed are the THC, NO_X CO_2 and PN (see **Figure 49**,**50** and **51**). No CO measurement was available for Diesel vehicle at Tcoolant=0°C.

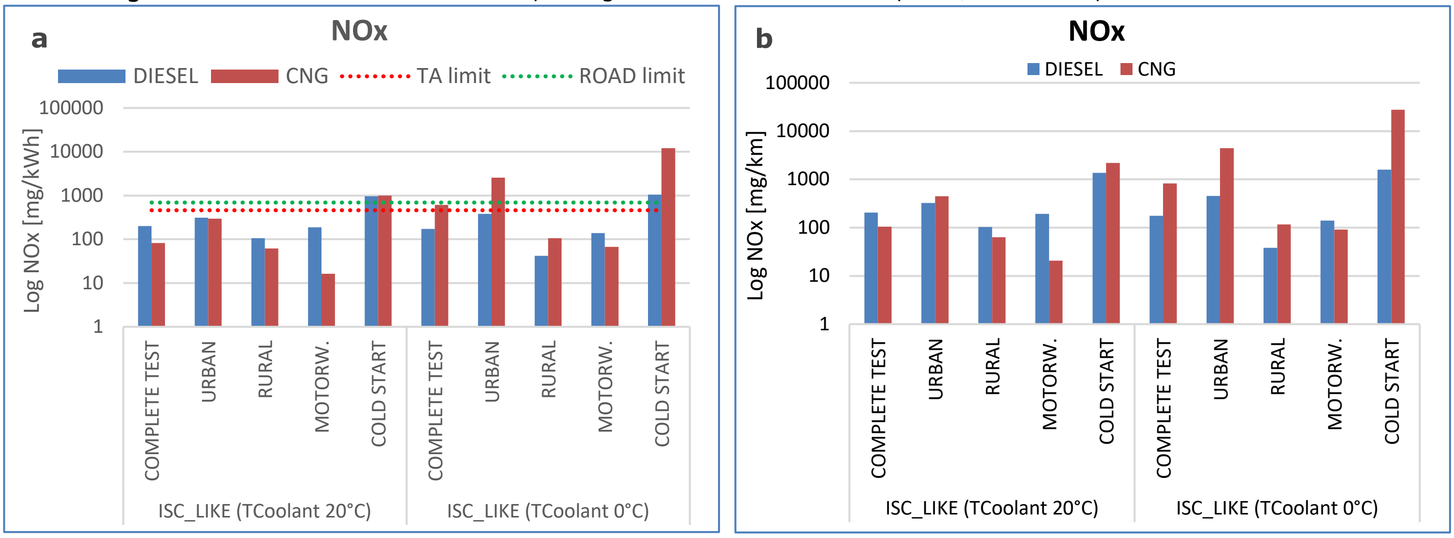
As prescribed by the Regulation (EU)582-2011 the reference temperature for evaluating a cold start event is that of the Coolant temperature. In detail, we will analyse the ISC_LIKE test, focusing our attention on the emission assessment passing from a coolant temperature of 20°C (our reference) to a coolant temperature equal to 0°C. In our tests a lower coolant temperature was a synonymous of a lower ambient temperature.

Figure 49. THC Emission Factor ISC_LIKE cycle (logarithmic notation). **a**: brake specific; **b**: distance specific.



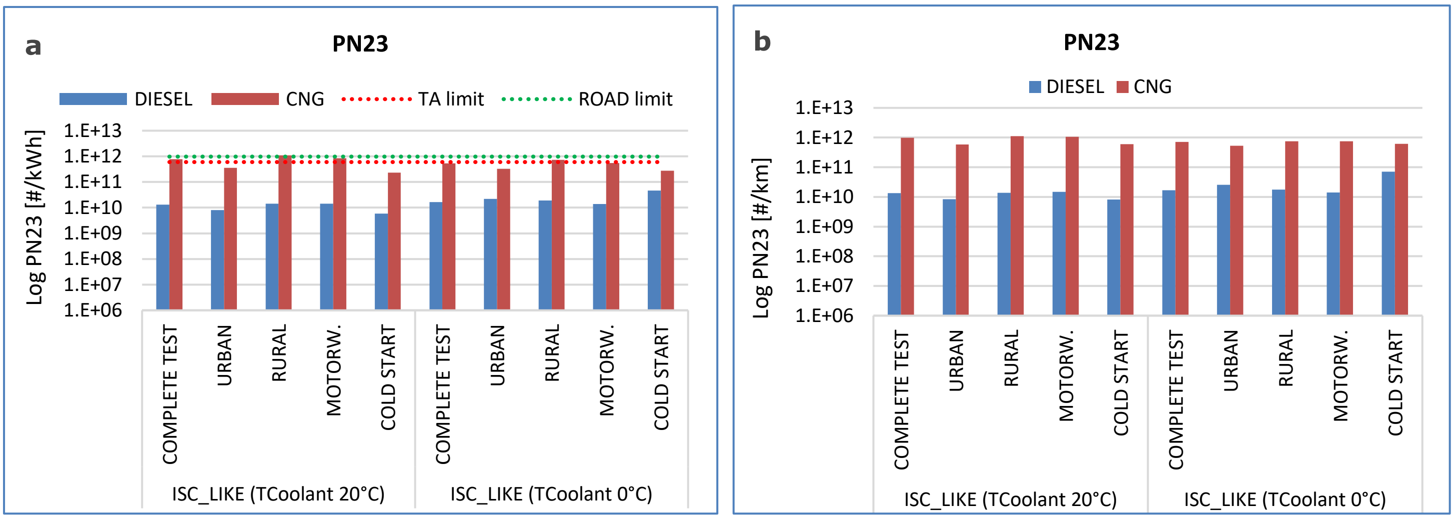
Source: JRC Vela, 2019

Figure 50. NO_x Emission Factor ISC_LIKE cycle (logarithmic notation). **a**: brake specific; **b**: distance specific.



Source: JRC Vela, 2019

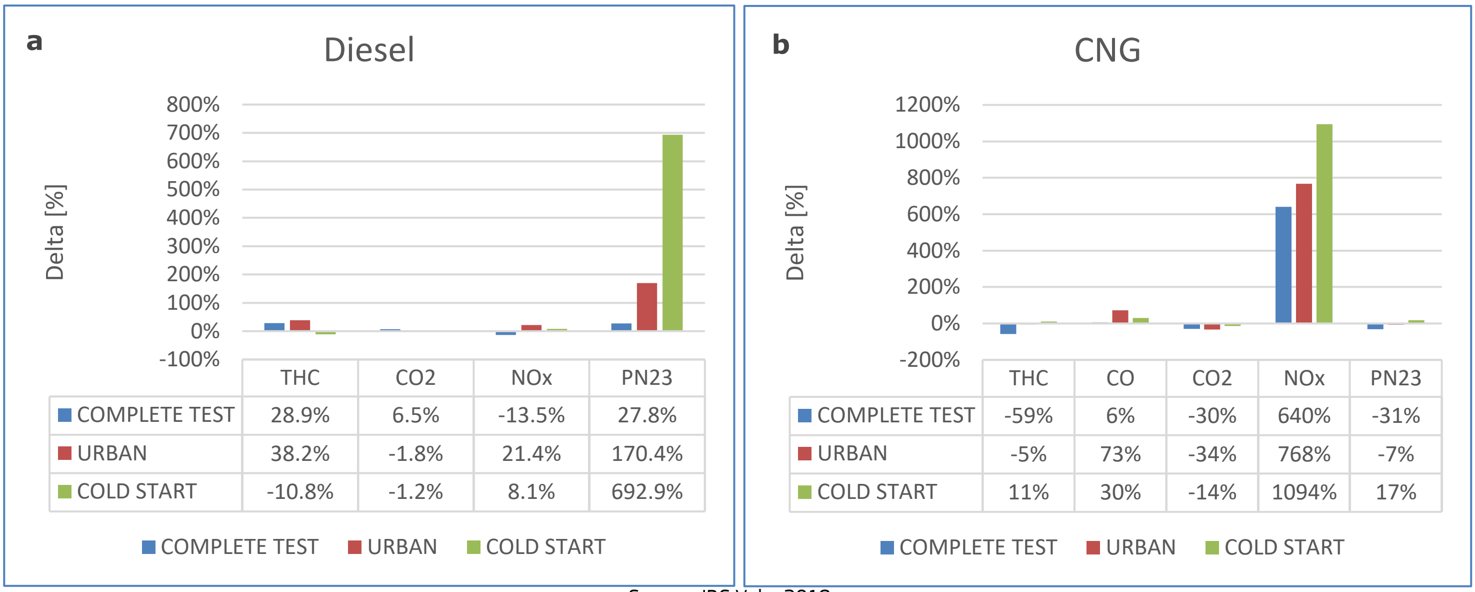
Figure 51. PM Emission Factor ISC_LIKE cycle (logarithmic notation). **a**: brake specific; **b**: distance specific.



Source: JRC Vela, 2019

Figure 52 depicts more clearly than previous graph the percentage difference (DELTA), pollutant by pollutant, in function of the coolant temperature for both tested vehicles (**a**: Diesel; **b**: CNG). Assuming the coolant temperature of 20°C as reference, the behaviour in the ISC_TEST has been verified with particular attention to the complete test, as well as to URBAN part and the cold start phase. A positive percentage means that the emission of the pollutant in question became worst, as the coolant temperature - or indirectly the ambient temperature – decreased.

Figure 52. Delta percentage in function of the coolant temperature (Tc) Tc=0°C vs Tc=20°C (reference).



a Diesel

	THC	CO2	NOx	PN23
COMPLETE TEST	28.9%	6.5%	-13.5%	27.8%
URBAN	38.2%	-1.8%	21.4%	170.4%
COLD START	-10.8%	-1.2%	8.1%	692.9%

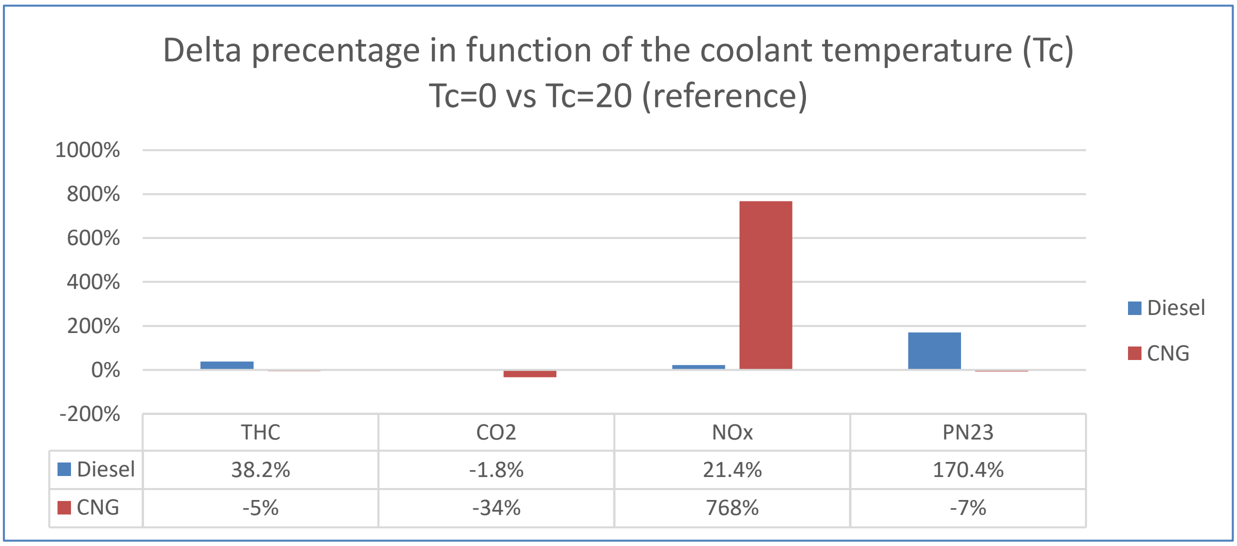
b CNG

	THC	CO	CO2	NOx	PN23
COMPLETE TEST	-59%	6%	-30%	640%	-31%
URBAN	-5%	73%	-34%	768%	-7%
COLD START	11%	30%	-14%	1094%	17%

Source: JRC Vela, 2019

The percentage comparison (DELTA) revealed important information: a big increase in the PN emitted by the Diesel truck with the decrease of the starting coolant temperature (and, in general, of the ambient temperature) registered before switching on the engine. This means that during the cold winter days, we should expect a substantial increase of the PN values in Diesel truck (the reference). Regarding the CNG engine, it was possible to observe a huge increased of the NO_X pollutant decreasing the coolant temperature.

Figure 53. Delta percentage in function of the coolant temperature. Diesel vs CNG vehicles on ISC_LIKE URBAN cycle.



	THC	CO2	NOx	PN23
Diesel	38.2%	-1.8%	21.4%	170.4%
CNG	-5%	-34%	768%	-7%

Source: JRC Vela, 2019

Highlighting the URBAN part of the ISC_LIKE test (see details in **Figure 53**), which represented the most interesting phase from the city behaviour stand point, the consideration before discussed are still valid. In Diesel engine we had an increase of the PN (+170.4%) and a huge amount of the NO_X emitted by the CNG truck (+768%). It is good to underline that the Diesel NO_X value were very low, this explains the high differential percentage; but it can be said that a substantial increased has been registered. PN has undergone an almost negligible decrease in CNG engine with lower coolant (and ambient) temperature (-7%). With a lot of cautions, these considerations could be extrapolated also to the CITY_MILAN cycle.

These data should be validated and confirmed by a dedicated campaign, as the few tests done at lower temperature did not permit to have a clear perspective of the phenomenon, and hence it did not allow to draw solid deductions and conclusions.

At the moment it is not possible to make better quality considerations. A project for a massive testing campaign, taking into account different cold start conditions (within 0 and 30°C) in the In-Service conformity of heavy-duty vehicles, has already been launched and it will be the subject for a future JRC investigation.

5.5 Regeneration (only Diesel vehicle)

Another topic that needs to be considered in an overall comparison between Diesel and CNG truck is the possibility to have a regeneration in the Diesel vehicle. During regeneration the emissions are higher and this should be taken into account in the overall emission of the vehicle. **Table 14** summarizes the emissions during the motorway part where regeneration took place. For the same time period the motorway emissions of non-regenerating cycles are given. For the specific vehicle regeneration was triggered after approximately 1400 km of driving. The regeneration lasted <30 min during the motorway driving (<40 km), thus a first approximation to include the regeneration missions would be to increase the emissions without regeneration by 40/1400 (3%) of the emissions during the regeneration. In fact, there is an approximately 200 mg/kWh increase of the NO_X emissions, and 3 orders of magnitude increase of the PN [**20**].

For gaseous pollutants the contribution is negligible. For PN the regeneration would bring the emission levels to 5-6×10^{11} p/km. The results are in agreement with a study on PN regeneration emissions from heavy-duty vehicles [**16**, **20**].

Table 14. Emissions during the motorway session (M) with and without regeneration.

Pollutant	Laboratory		On-road	
Regeneration	No	Yes	No	Yes
Distance (km)	43.3	43.6	41.6	39.8
CO (mg/km)	250	583	1160	905
NO_X (mg/km)	17	287	271	395
HC (mg/km)	0	1	0	4
PN ×10^{11} (#/km)	0.15	119	0.19	144
T_{exh} (°C)	226	448	194	385
T_{SCR} (°C)	264	508	249	494

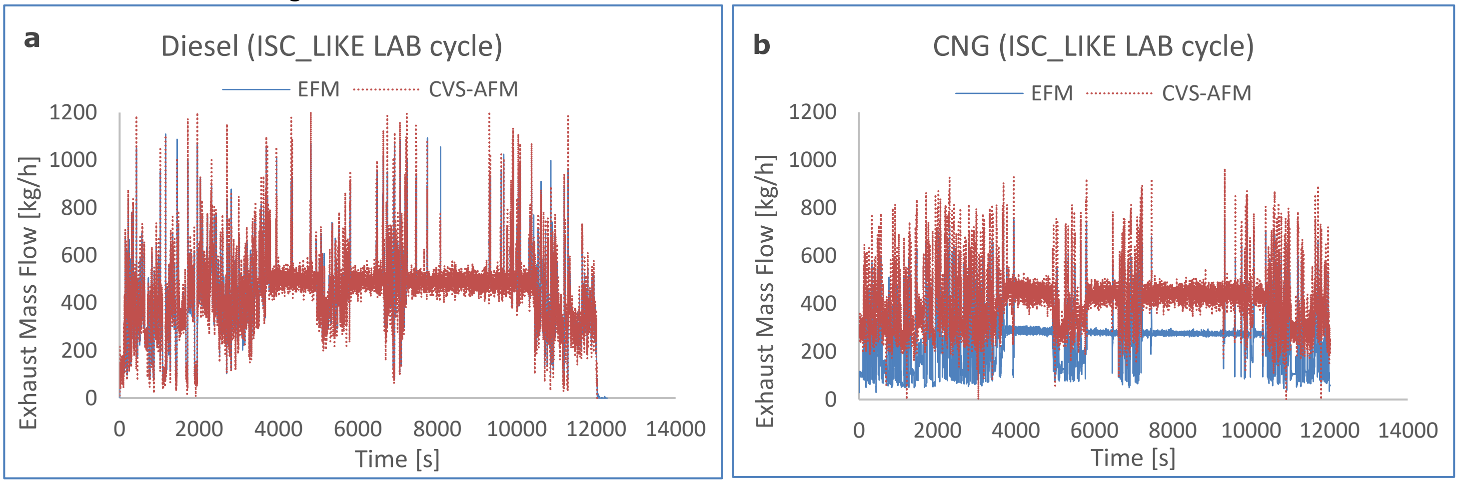
Source: JRC, 2019 [**20**]

6 Proposal of a correction for CNG exhaust mass flow

This session addresses the possibility to correct the CNG exhaust flow in the light of the results obtained and the consideration made during the PEMS assessment (see **Paragraph 4.2**).

Considering the laboratory test, in the ISC_LIKE test presented in **Figure 54**, it is clear that there was a very good correlation between the exhaust mass flow measured by EFM and the estimated exhaust mass flow by the dilution tunnel (CVS-AFM: total diluted flow minus dilution air flow) in the Diesel vehicle (**Figure 54a**) while it is not true for CNG truck (**Figure 54b**). In fact, the average difference, considering all the ISC_LIKE analysed cycles, was respectively less than -2% for Diesel and around -40% for CNG.

Figure 54. Exhaust Mass Flow: EFM measured vs dilution tunnel estimation. **a:** Diesel; **b:** CNG.

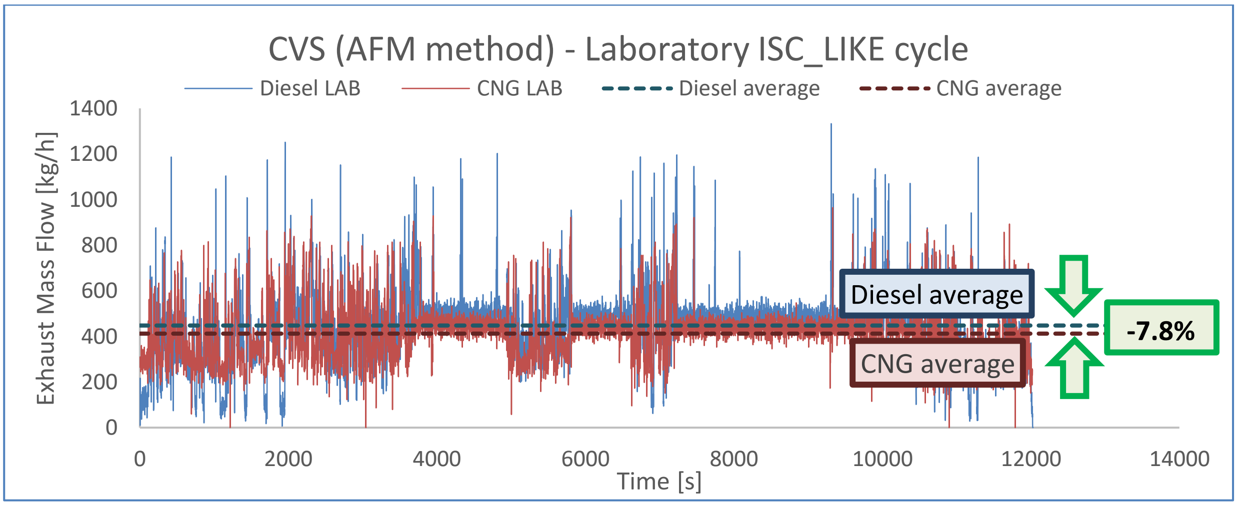


Source: JRC Vela, 2020

6.1 Target baseline

As first step to identify a reliable correction, it has been necessary to individuate a target baseline. The target baseline was defined by observing the variation between the estimated exhaust mass flow by the dilution tunnel (total diluted flow minus dilution air flow) between Diesel and CNG vehicle in the laboratory cycles. As assumption, it reasonable to think that similar variation could be expected also in the real-word behaviour (road). The detected average difference was in the range -7÷-8% for all the ISC cycle examined (-7.8% for the one plotted below in **Figure 55**).

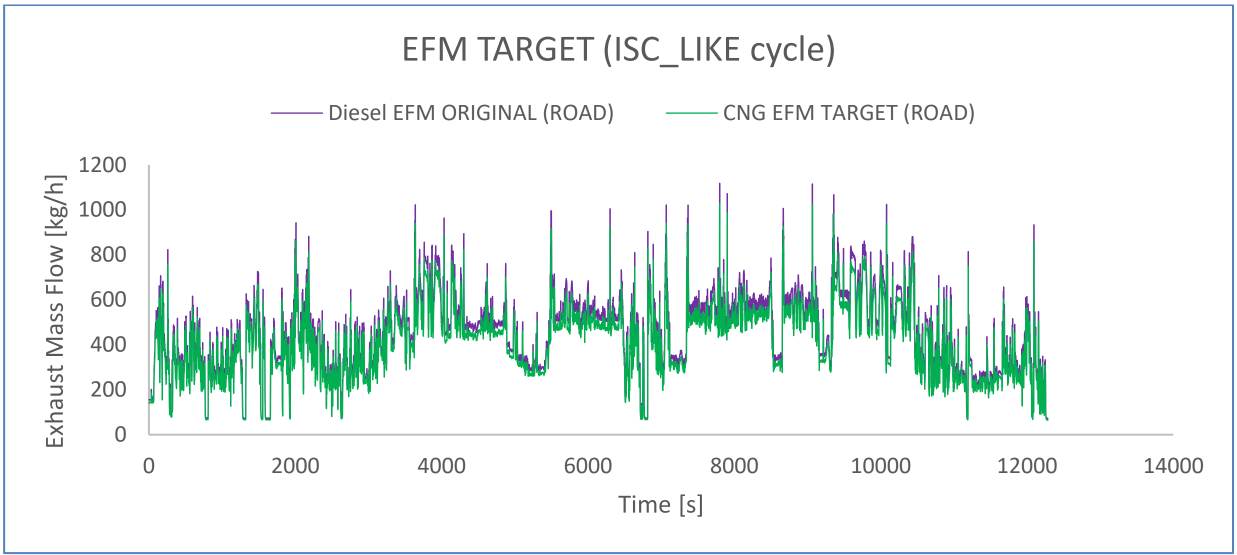
Figure 55. Average difference between the Diesel and CNG Exhaust Mass Flow estimated by the dilution tunel in ISC_LIKE cycle performed in VELA_7 laboratory.



Source: JRC Vela, 2020

As explained below in **Figure 56**, the CNG target baseline in road conditions is obtained starting from the Exhaust Mass Flow measured by the EFM in the Diesel vehicle applying the same difference percentage detected in laboratory tests between the two trucks using the tunnel dilution values (the reference values, also called CVS-AFM method values). In this case, only the ISC_LIKE cycles has been considered. The constant average percentage was -8% obtained as a mean of all ISC_LIKE cycles investigated in the laboratory for the respective vehicles.

Figure 56. Determination of EFM TARGET baseline for CNG vehicle in road condition



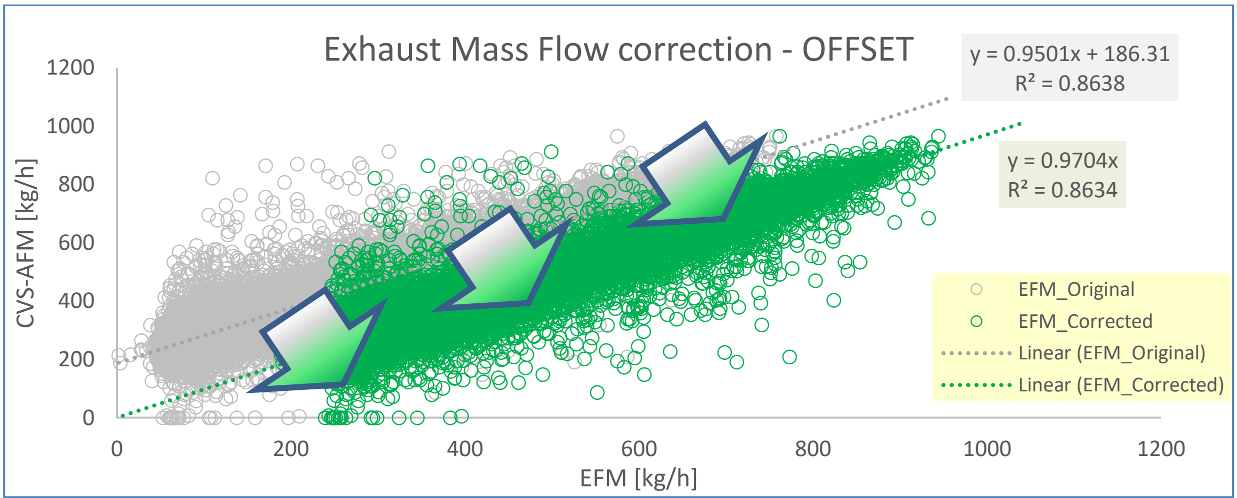
Source: JRC Vela, 2020

The green line represents the target baseline proposed for the CNG EFM measurement in road condition.

6.2 Correction algorith

At glance, comparing all the tests performed in laboratory, it means all the ISC_LIKE and all the CITY_SIM tests, it seemed that a sort of offset was present between the EFM measurement and the CVS-AFM method estimation. See in **Figure 57** the original data in grey towards the corrected one in green.

Figure 57. Exhaust Mass Flow correction applicable to the CNG vehicle in road condition - OFFSET



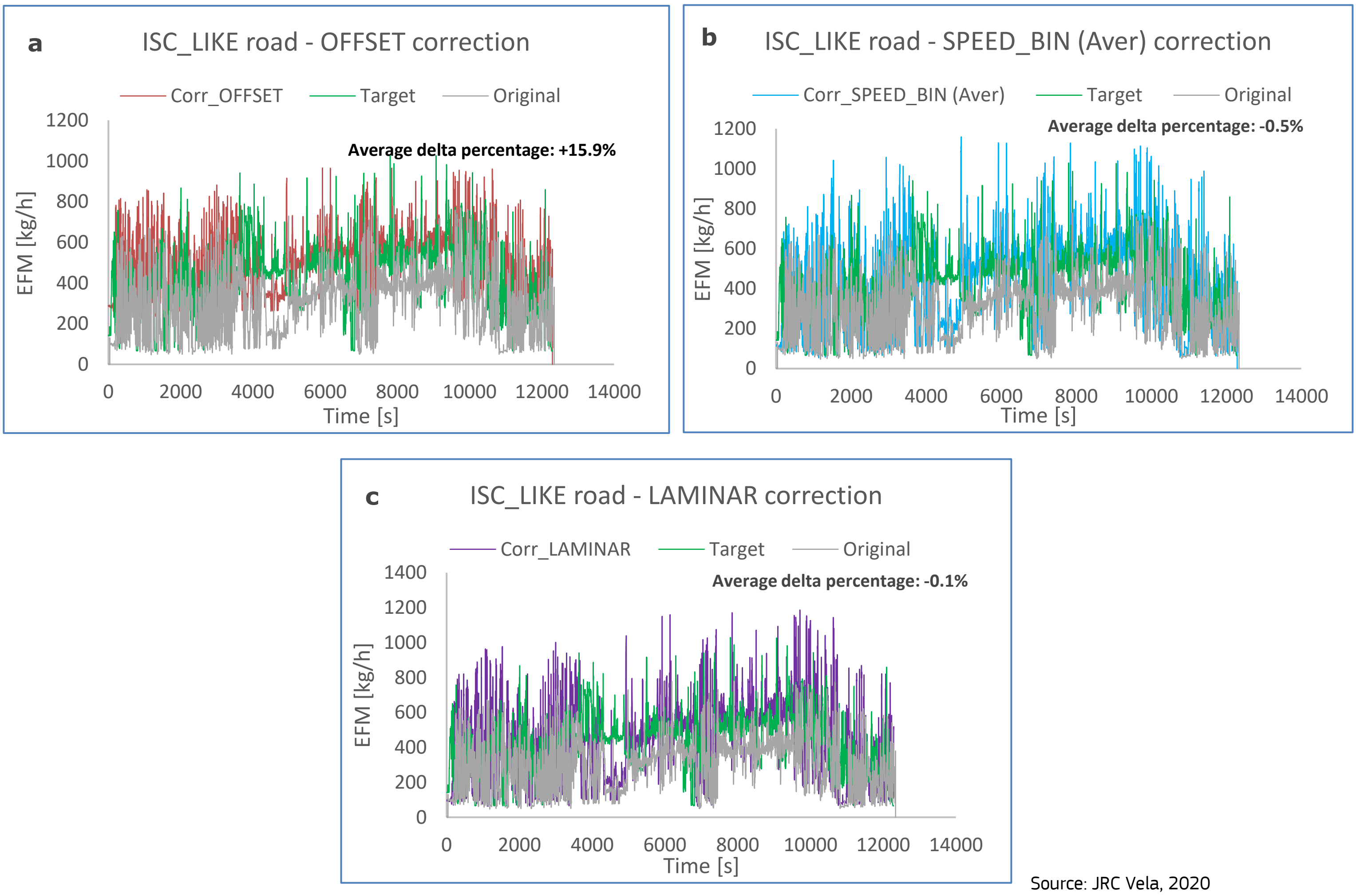
Source: JRC Vela, 2020

Figure 57 depicts a theoretical calculated OFFSET of 186.31 kg/h that it was supposedly necessary to add to the original flow to reach a proper linearity correspondence to try to approximate the TARGET baseline. Despite the correction appeared theoretically pretty good, in reality during the road tests the situation varied too much to use this simplistic way. The exhaust mass flow measurement seemed to be correlated also to the previous history before the test starting (ambient temperature, vehicle conditioning, etc..) more in road conditions than in laboratory. A series of possible corrections have been explored. Among the others, the variation of the EFM in function of the engine speed bins parameterized by the torque values in the bin itself gave reliable results only in a short range of engine speeds (not reported in the following discussion). An approximation which better fitted with the target baseline, without introducing unnecessary complications, was to divide the vehicle speeds during every tests in different bins, equivalent to the speed classification already used to recognize the diverse phases of the test. It means the Urban (U), Rural (R) ad Motorway part (M) using the same ranges prescribed by the Regulation(EU) 582/2011[**7**]. This last correction technique has been called SPEED_BIN (Aver) method, since corrected in percentage every average bin. A fourth correction which considered the flow as a laminar fluid has been also introduced (this compensation was called LAMINAR). In the following discussion, two cases at the extremes (minimum and maximum correction) will be presented.

6.2.1 Case study: ISC_LIKE cycle

In this paragraph a comparison among the OFFSET, the SPEED_BIN (Aver) and the LAMINAR correlations is presented. As stated in **Figure 58**, the OFFSET correlation method tends to overestimate the Exhaust Mass Flow, while the SPEED_BIN (Aver) and the LAMINAR methods underestimate it. Considering the overall cycles, a delta percentage [(Corrected value - Target value)/Target value] of +15.9%, -0.5% and -0.1% have been registered respectively for the OFFSET, the SPEED_BIN (Aver) and the LAMINAR compensations. These percentages gave us a roughly idea of the goodness of the two correction approach. It is evident that the second approach gave better results.

Figure 58. CNG Exhaust Flow correction methods. **a:** OFFSET; **b:** SPEED_BIN (Aver); **c:** LAMINAR.



Source: JRC Vela, 2020

Introducing the corrected exhaust flow, estimated as above described, in the routine calculations, it is thinkable that the final effect, in terms of increasing of the overall emission factors, should be impressive for the CNG vehicle. Only the SPEED_BIN (Aver) compesation will be analysed. **Table 15** summarizes the percentual increasing of the Exhaust Mass Flow after the correction for all the speed bins considered.

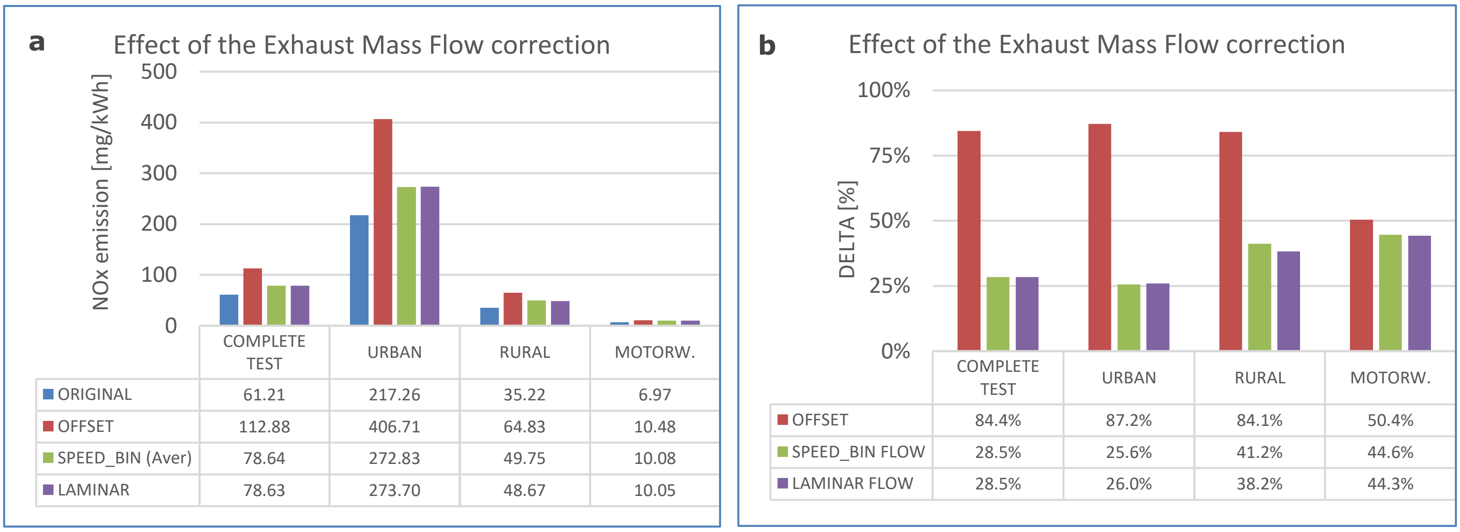
Table 15. EFM percentage increasing per speed bin (Aver) correction.

ISC_LIKE	EFM average variation [%]
COMPLETE CYCLE	38%
U	27%
R	55%
M	41%

Source: JRC Vela, 2020

As an example of the significant increasing due to the flow correction, in **Figure 59** the NO_X variation is presented when the different compensation algorithms have been applied to a single ISC performed in the road. The cycle is the same already shown in **Figures 58**.

Figure 59. Effect of the different Exhaust Mass Flow corrections analysed applied to a ISC_LIKE cycle. Effect correction in terms of brake specific emission (**a**) and delta percentage (**b**).

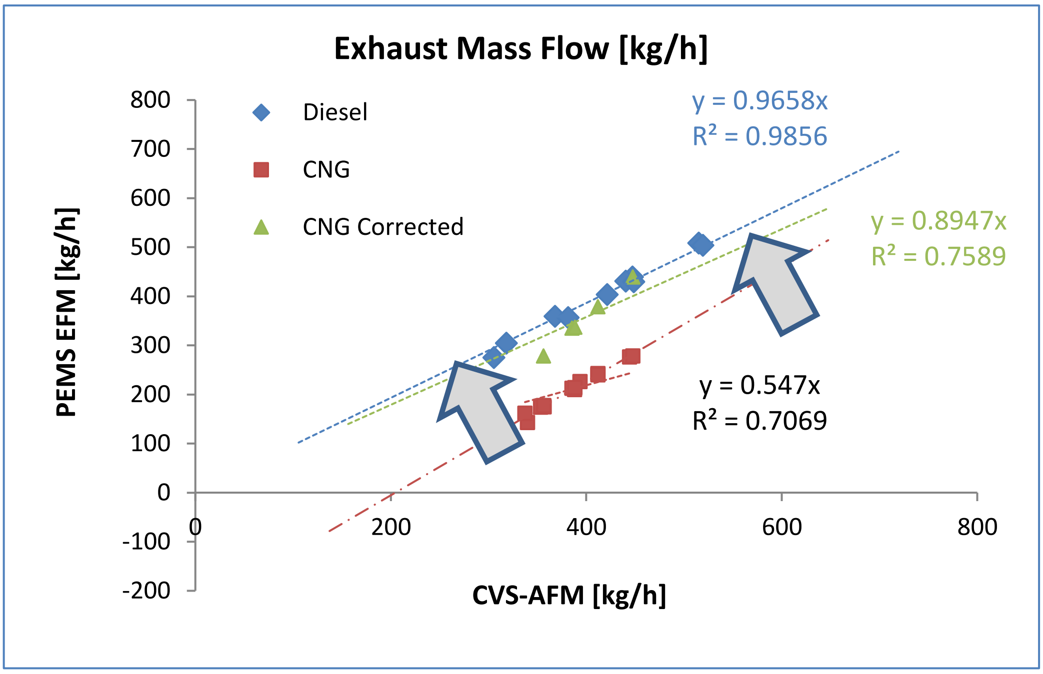


Source: JRC Vela, 2020

Analysing the reliability of the different corrections, it is prominent to observe that the OFFSET correction, as easily predictable, introduced a too high variation, due to the fact that the flow corrected with this method is highly overestimated. The SPEED_BIN (Aver) and the LAMINAR corrections gave very close results, that is an increase of the NO_X emission factors of 28.5% in the complete test cycle and breakdown the cycle into the three main phases, an increase of around 26%, 40%, 45% respectively in Urban, Rural and Motorway part. The same percentage increases are valid also for all the other pollutants.

Figure 60 depicts the correlation between the Exhaust Mass Flow values measured by the EFM and the ones estimated by the dilution tunnel ones (CVS-AFM). The effect of the correction is considerable. In the graph below, only the ISC tests performed in the laboratory are plotted. Also, the Diesel exhaust emission values have been reported as comparison reference.

Figure 60. Effect of the correction in the Exhaust Mass Flow. Comparison between PEMS and CVS-AFM in laboratory tests.

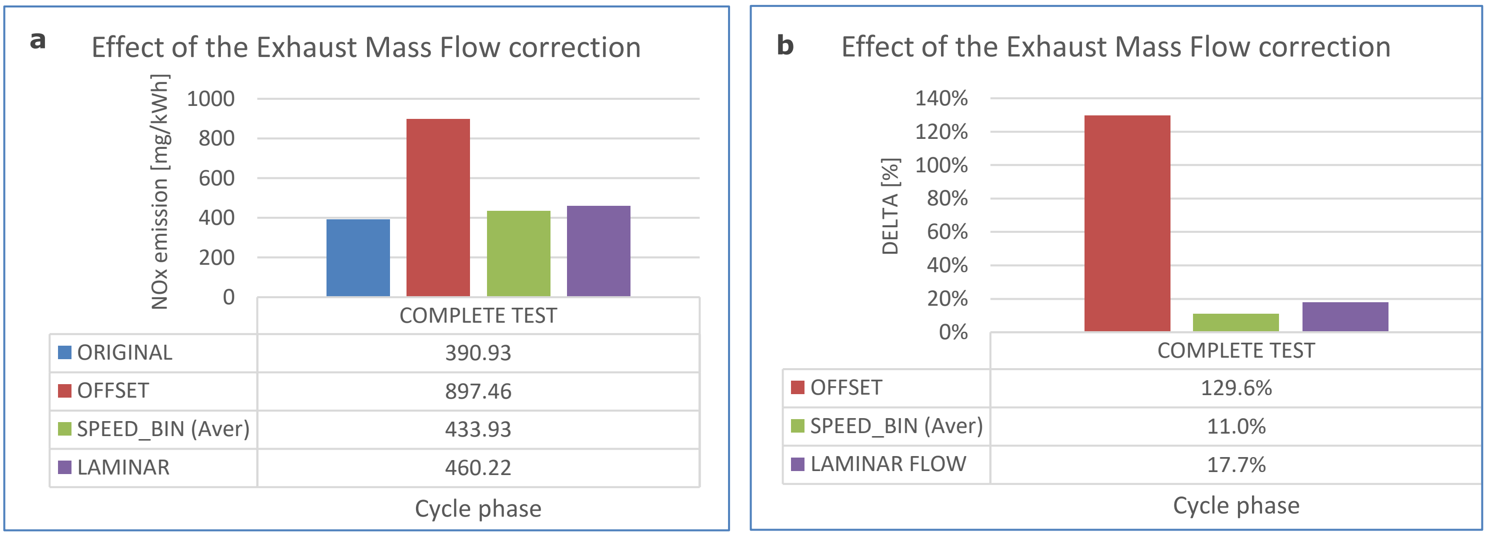


Source: JRC Vela, 2020

6.2.2 Case study: CITY_SIM cycle

In the following paragraph, a second case is presented without entering into the details of the baseline target creation. The different corrections are applied to a single CITY_SIM cycle test. As in the previous example, the OFFSET correction did not give reliable results, while both the SPEED_BIN (Aver) and the LAMINAR methods gave more credible results (see **Figure 61** for reference). **Table 16** gives a synoptic of the EFM percentage increasing using the SPEED_BIN (Aver) correction.

Figure 61. Effect of the different Exhaust Mass Flow corrections analysed applied to a CITY_SIM cycle. Effect correction in terms of brake specific emission (**a**) and delta percentage (**b**).



Source: JRC Vela, 2020

In the CITY_SIM route, the complete test cycle corresponded entirely only to an urban phase, for this reason no Rural and Motorway parts are reported.

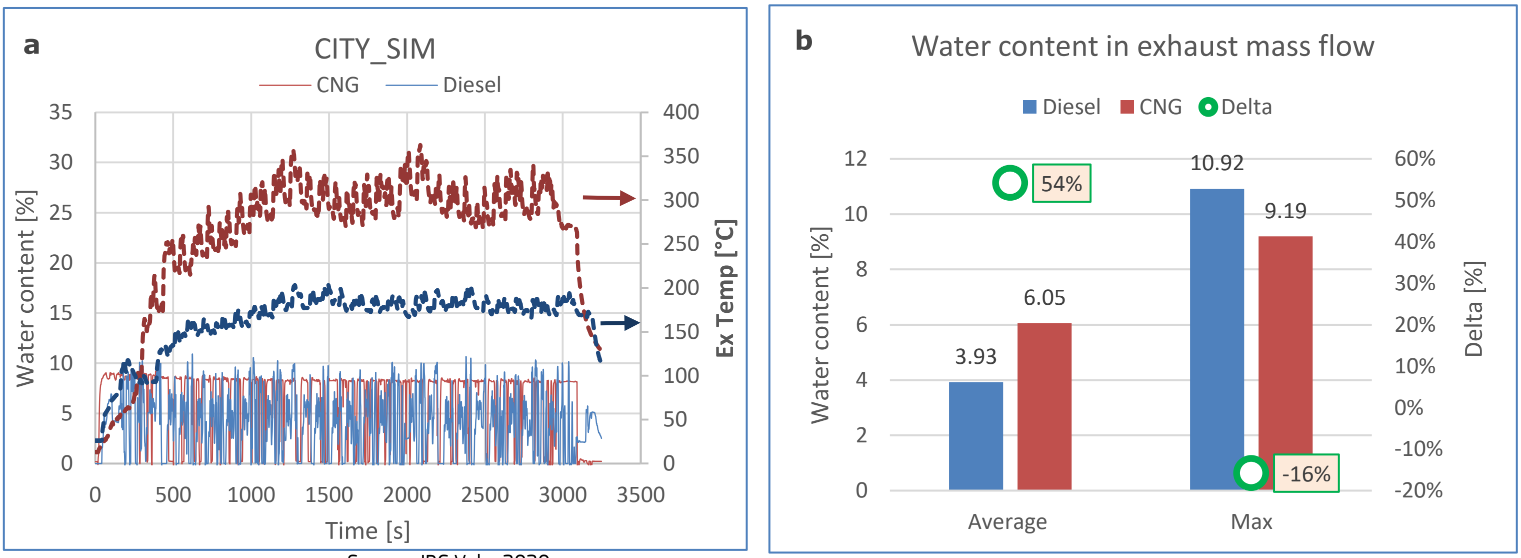
Table 16. EFM percentage increasing per speed bin (Aver) correction.

ISC_LIKE	EFM average variation [%]
COMPLETE CYCLE (URBAN)	11%

Source: JRC Vela, 2020

An explanation of the different behaviour between the ISC_LIKE and the CITY_SIM cycle could be found in the different percentage of the condensable water vapour content. Despite of the high difference registered in ISC_LIKE test (see **Paragraph 4.2**), the average water content percentage for the Diesel vehicle and the CNG vehicle in CITY_SIM cycles were very similar, respectively 3.93% against 6.05%. In this case, even if the delta percentage was very high, what it was important were the values in absolute terms far from a level that could be perturb the reading of the Exhaust Mass Flow measured by the EFM equipment see **Figure 62** for further details).

Figure 62. Condensate water vapour content in percentage at the exhaust flow in correspondence of the PEMS probe. **a:** ISC_LIKE example cycle; **b:** Average and maximum content in the ISC cycle.



Source: JRC Vela, 2020

7 Technology improving impact on emission performances

Air pollution coupled with more and more restrictive requirements concerning the emission of hazardous exhaust gases cause that truck fleets in towns and also in non-urban traffic are changing considerably. In large urban areas the content of hazardous substances usually exceeds standard levels.

The requirements on the level of exhaust emissions are laid down in international and European standards. The Euro V and EEV regulations entered into force in 2009 and implemented by way of Directive 2005/55/EC of 28 September 2005. Starting from 2014 the new Euro VI standard is in force, as set forth in Regulation no. 595/2009 and in the EEV standard, as well as its implementing Regulation(EU)582/2011 [**7**], with further amendments contained in Regulation 133/2014. The Euro VI emission limits went into effect in 2013 for new type approvals and in 2014 for all registrations. In real conditions of traffic, at the values of admissible emissions may be applied an additional factor exceeded for instance for CO, HC and NO_X 1.5 times as Regulation(EU)582/2011 [**7**] foreseen. This not means that the admissible emission can exceed the limits proposed, since these limits take into account the different testing condition passing from laboratory to the road, e.g. different equipment, diverse boundary conditions, etc. (see previous discussion in **Chapter 5**).

The tightening of regulations and the implementation of stringent legislated reduction of exhaust gas emission, obliged the truck engine and vehicle companies (in the latter called Original Equipment Manufacturers – OEMs) to experiment and to launch new technical solutions.

7.1 Euro V/EEV vs Euro VI

Annex 1 and **Table 17**, below, shows the emission limits for the Euro V and Euro VI standards. As with light-duty vehicles, the move from Euro V to Euro VI saw a large reduction in the NO_X emission limit, from 2.0 g/kWh to 0.4 g/kWh in steady-state testing, and from 2.0 g/ kWh to 0.46 g/kWh in transient testing, or reductions of 80% and 77% respectively. The particle mass limit was also significantly tightened, cut in half from 0.02 g/ kWh to 0.1 g/kWh on steady-state testing, and from 0.03 g/kWh to 0.01 g/kWh on transient testing, a reduction of 66%.

The Euro VI standards (see **Annex 2** for additional information) include for the first time a particle number limit. The limit is 8×10^{11} particles per kilowatt-hour under the WHSC test, and 6×10^{11} under the WHTC test. The vehicle certification test cycle to meet the Euro VI standards is different from that used for Euro V, so the comparisons are only approximate.

The Euro VI standards also set emission limits for ammonia since the tighter NO_X standard will require the use of Selective Catalytic Reduction after-treatment (Diesel engines), which in turn relies on the injection of urea into the exhaust stream. The catalytic reaction can produce ammonia as an unwanted by-product, hence the limits on ammonia emissions for heavy-duty diesel (CI) vehicles (gasoline vehicles, also called "Spark Ignition" vehicles, are exempt from the ammonia limit since urea is not used for NO_X control, even if the SI engines fuelled by Natural Gas (NG or CNG) emitted a lot of Ammonia, as reported in **Paragraph 5.2.6**. The Euro VI standards include a methane emission limit for "positive-ignition" (SI) vehicles (i.e., not diesels, but specifically natural gas and liquefied petroleum gas engines) based on the emergence of natural gas-powered vehicles in the heavy-duty vehicle sector and the potential impacts of methane on tropospheric ozone. For Hydrocarbons, we have considered the total amount without distinguishing between NMHC and Methane compounds, using the limit foreseen for compression ignition (CI) engines.

Table 17. The Euro V and Euro VI Heavy-Duty Vehicle (HDV) emission standards for Diesel and CNG engines.

	Heavy-Duty Vehicles transient cycle	
Emission limits [g/kWh]	Euro V	Euro VI
CO	4	4
HC	0.55	0.16[a]
CH_4[a]	1.1	0.5
NO_X	2	0.46
PM	0.03	0.01
PN [#/kWh]	-	$6.0x10^{11}$
Ammonia [ppm]	-	0.01
Fuel Sulphur limit [ppm]	10	10
Test cycle	ETC	WHTC

a) For Euro V Natural Gas only, for Euro VI NG and LPG

b) Total HC for Diesel engines, non-methane HC for others

Source: JRC Vela, 2019

7.1.1 Different technical approach between Euro V and Euro VI

In Diesel Engines, Euro VI standards have been met by manufacturers through a combination of DPF and SCR technologies, in addition to DOCs, EGR and other advanced engine technologies. The move to a combination of DPF and SCR technologies requires a switch from Vanadium to Zeolite catalysts for the SCR systems. The end result of this technology change and the improved test cycle is that real-world NO_X emissions much more closely match the emissions limits than was the case with previous standards, especially at low vehicle speeds and cold start conditions.

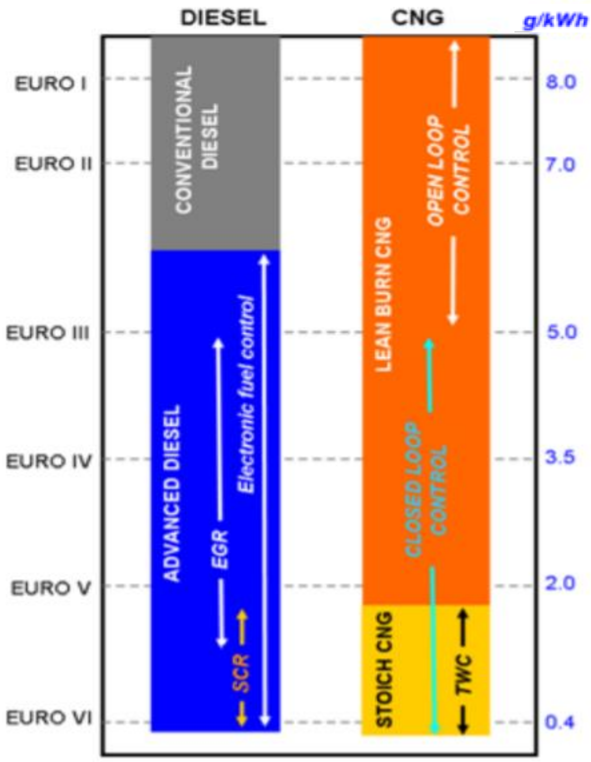
Euro VI standards also require OBD systems to measure performance of emission control systems in use and to provide early identification of any system failures. These systems operate in addition to the driver inducements for use of urea additives that are necessary for the proper operation of SCR systems required in Euro V.

For achieving the Euro VI emission limits for HD CNG engines, manufacturers explored the possibility to switch to stoichiometric combustion combined with exhaust gas recirculation (EGR) and three-way catalyst (TWC) after-treatment. A stoichiometric engine does not have inherently lower engine-out NO_X emissions than a lean-burn engine, but the stoichiometric combustion mixture allows the use of a TWC. A TWC cannot be used on a lean burn engine (either diesel or CNG) because exhaust oxygen levels are too high, which not allows for NO_X reduction during rich periods of operation. Exhaust gas recirculation (EGR), a technology borrowed from diesel engine emission control technologies, was employed to curb the excessive high temperature and heat production in the stoichiometric CNG engine. Further improvements can be achieved by adding a camless hydraulic valve actuation (HVA) system to improve efficiency. The use of the HVA system was introduced to increase the CNG efficiency by reducing the pumping losses.

The voluntary EEV (enhanced environmentally friendly vehicle) standard was first introduced in 1999. The EEV standard is slightly lower for PM and CO emissions limits over the transient test cycle, but does not require any additional vehicle or after-treatment technologies compared to Euro V.

Figure 63 gives a synoptic overview of the main technological changes between the different Euro stage [**58**]. **Table 18** summarized the main variations passing from Euro V to Euro VI regulation.

Figure 63. Technology evolution of heavy-duty engines to meet more stringent emission standards in the EU.



Source: theicct.org, 2009

Table 18. Compliance approaches for heavy-duty Euro V and Euro VI engines.

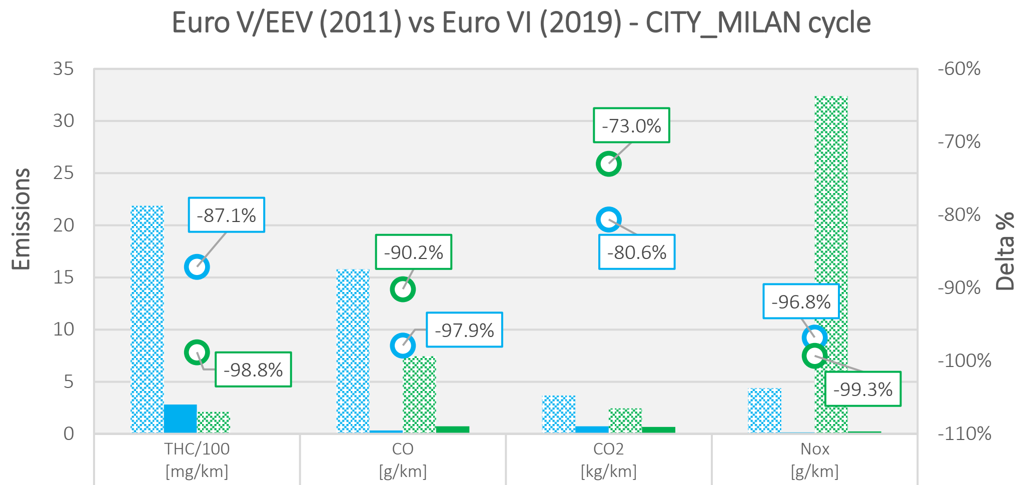
Euro V	Euro VI
Diesel	
High fuel injection pressure	DPFs required for Euro VI compliance with PM and PN standards
Variable fuel injection timing and quantity	SCR catalyst changed from Vanadium to Zeolite
Redesigns to combustion chamber	ECR no longer offered
NO_X controlled mainly by SCR-Vanadium based systems	
EGR offered by few manufacturers and mainly for small trucks	
CNG	
	TWC can be applied as the after-treatment device
Lean burn	Stoichiometric combustion
Open/Closed loop control	Closed loop control
	EGR requires an intercooling circuit
	Efficiency improves using camless hydraulic valve actuation (HVA)
	Throttle-body injection (TBI) or port fuel injection (MPFI)

Source: theicct.org, 2019

7.2 Impact of the latest updated regulation on refuse collection vehicles emission assessment

The figures and values in the following graphs might show slight differences with the data till now reported (see **Chapter 7**). In this analysis, we have considered different average values sometime based only on a single test. The attention was focused on the CITY_MILAN cycle. In this investigation only distance specific emissions have been used (i.e. in g/km), as in the previous study [**5**] the test has been performed mainly using this metric.

Figure 64. Comparison between the refuse vehicle campaign 2011 and testing campaign 2019 results in CITY_MILAN cycle (Euro V/EEV vs Euro VI).



	THC/100 [mg/km]	CO [g/km]	CO2 [kg/km]	Nox [g/km]
CNG EEV	21.88	15.81	3.68	4.38
CNG_EURO VI	2.82	0.33	0.71	0.14
DIESEL EURO V	2.10	7.44	2.45	32.39
DIESEL EURO VI	0.02	0.73	0.66	0.22
Delta % CNG (EEV/EURO VI)	-87.1%	-97.9%	-80.6%	-96.8%
Delta % DIESEL (EURO V/EURO VI)	-98.8%	-90.2%	-73.0%	-99.3%

Source: JRC Vela, 2019

Obviously, the tightening of regulations and the implementation of more stringent exhaust gas emission limit, represented a strong push to introduce new technologies and strategies. The results are clearly indicated in **Figure 64**, where it is possible to have a perception of the enormous improvements achieved by switching from the older regulation (Euro V-EEV) to the new one (Euro VI), even though a direct comparison is very difficult as the cycles and test methods have changed a lot between the two legislations.

With reference also to **Figure 65** and **66**, that better underline the situation case by case, the vehicles that benefited the most from the update of the directives regarding the reduction of gaseous emissions at the tailpipe of vehicles, was the Diesel one for some aspects and the CNG for others.

Regarding CO and CO_2, the CNG trucks benefited furthered in the reduction in their emission with higher percentage of decrease, however all these pollutants were largely within their respective limits, on the other hand, THC percentage reduction was higher in the Diesel truck.

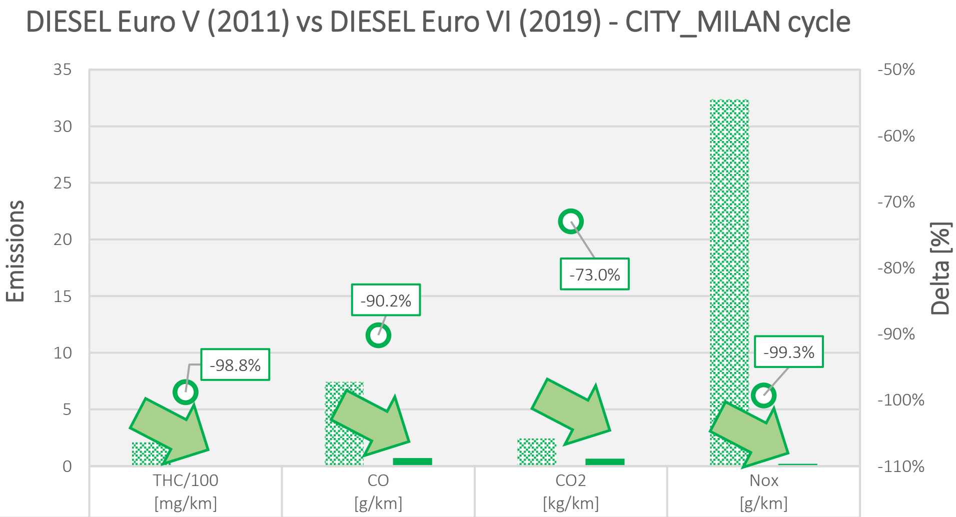
Extrapolating these partial results, it is possible to deduct that in changing technology, the CNG RCV (Refuse Collection Vehicles) saved 87.1%, 97.9% and 80.6%, while Diesel RCV saved 98.8%, 90.2% and 73% respectively for THC, CO and CO_2 emissions. Despite the differential percentage, the CNG absolute starting values assessed under Euro V/EEV regulation was higher than the Diesel ones, so for these pollutants the progress in CNG application was the largest.

The situation is opposite from the NO_x point of view. In the comparison, the NO_x Diesel initial value – that is referring to Euro V/EEV- were 8 times the CNG one (32.39 vs 4.38 g/km).

Shifting technology, the saving was of 99.3% in Diesel against 96,8% in CNG. It was not possible to compare the PN performances, because in the previous study dated 2011, no PN measured were performed, since it was not regulated by the legislation.

Bearing in mind that heavy-duty vehicles have historically not achieved the real-world NO_X emissions expected under Euro V and previous standards, and considering, moreover, the high hazard given by NO_X compounds, in particular in a city environment and, consequently, the attention paid to this pollutant, it is conceivable doable to assume that a great leap forward was made especially in Diesel vehicles.

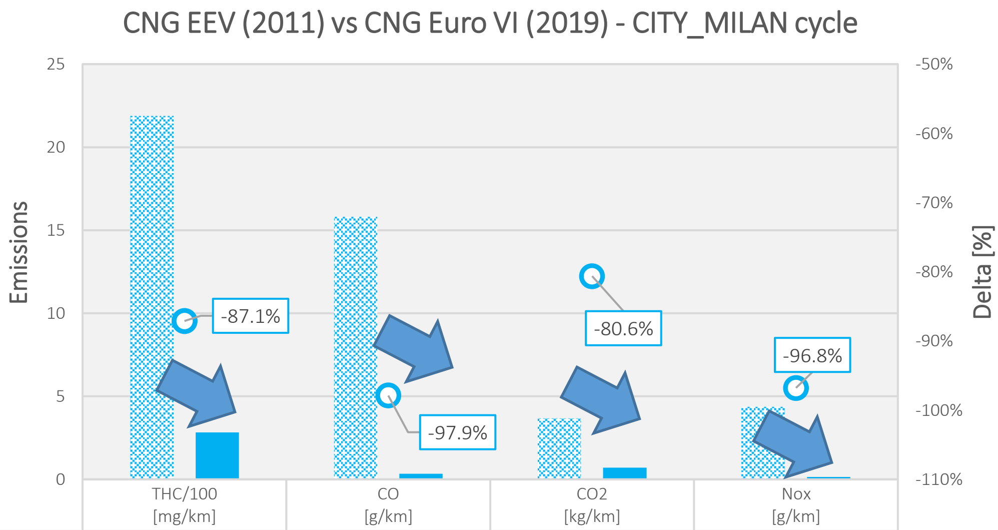
Figure 65. Diesel refuse collection vehicle behaviour in CITY_MILAN in function of the regulation in force (Euro V/EEV vs Euro VI).



	THC/100 [mg/km]	CO [g/km]	CO2 [kg/km]	Nox [g/km]
DIESEL EURO V	2.10	7.44	2.45	32.39
DIESEL EURO VI	0.02	0.73	0.66	0.22
Delta % DIESEL (EURO V/EURO VI)	-98.8%	-90.2%	-73.0%	-99.3%

Source: JRC Vela, 2019

Figure 66. CNG refuse collection vehicle behaviour in CITY_MILAN in function of the regulation in force (Euro V/EEV vs Euro VI).



	THC/100 [mg/km]	CO [g/km]	CO2 [kg/km]	Nox [g/km]
CNG EEV	21.88	15.81	3.68	4.38
CNG_EURO VI	2.82	0.33	0.71	0.14
Delta % CNG (EEV/EURO VI)	-87.1%	-97.9%	-80.6%	-96.8%

Source: JRC Vela, 2019

8 Conclusions

The report mainly addresses the outcome of the extensive experimental study, performed both under real-world and laboratory controlled operating conditions, aimed to identify the actual emission levels of the waste collection vehicles. Two different engine technologies (Diesel and Compressed Natural Gas fuelled engines) has been directly compared to assess the environmental efficiency of the different trucks solutions.

Tail-pipe emissions levels (NO_X, CO, HC, PN) of two Euro VI step C heavy-duty refuse collection vehicles were examined on the road using a portable emissions measurement system (PEMS) and on the chassis dynamometer, using in addition laboratory grade analysers and a Fourier-transform infrared spectroscopy (FTIR) system. Furthermore, also CO_2, Ammonia (NH_3) and Nitrous oxide (N_2O) were analysed.

The vehicles were tested on-road under conditions that did not necessarily comply with the official ISC test, with the aim of deriving real world emission factors of regulated pollutants.

A series of three different on-road test patterns has been developed:

1) ISC_LIKE: a test similar to an In-Service Conformity test, with different trip composition in terms of percentage time sharing. The "urban" part has been favoured by increasing its percentage.
2) CITY_SIM: custom-made cycle which simulates the operation of the vehicle in the city with start and stops and compaction activities (without compress any garbage).
3) CITY_MILAN: the vehicles operated under their normal daily routes under real-world conditions.

Finally, a comparison between ISC_LIKE and ISC_COMPLIANT cycles performed in the road has been provided to evaluate the distance between the ad-hoc ISC used in the campaign and a ISC compliant cycle. Further laboratory analysis has been introduced, however it has not been presented in this report, apart from the validation of PEMS instruments and the assessment of ammonia and N_2O emissions.

Since it was a comparison exercise, as methodology we decided to follow the guidelines provided by the Regulation(EU) 595/2009 and 582/2011 [**7**] for Euro VI step C heavy-duty trucks, with some exceptions, namely, also PN measurement has been added, no exclusion in the power demand and cold start has been considered.

Two reference limits were introduced where applicable (gaseous pollutants and solid particle):

a) TA limit: it is the applicable limit the engine has to fulfil during the type approval test performed at the engine dyno.
b) TA road: it is a sort of equivalent limit for the vehicle tested on road, taking into account a multiplication factor of 1.5 and of 1.63 time the TA limit, respectively for gaseous pollutants and PN. In reality, according to the same line proposed by the Regulation(EU) 582/2011 [**7**], these factors have to be used only in the evaluation of the Conformity Factors (CFs) and their validity is limited only to the Moving Average Window approach (see **Annex 5** for further details) and not on the average over the entire trip. The Conformity Factors in the RDE and in ISC test, respectively for light-duty and heavy-duty vehicles, give a concrete measure of the possible distance of the real emission factors from the laboratory values (e.g. at Type Approval), bearing in mind the difference of the measuring equipment, the variability of operations, as well as a number of boundary conditions not present in the laboratory, which inevitably make the test more severe. Even if not directly linked, nevertheless, we have enlarged this concept, adopting the same approach not only for the ISC cycles, but also for the other test cycles (CITY_SIM and CITY_MILAN).

The conclusion of the present study will be presented under some assumptions: a) Reported aggregate emissions values have been averaged using at least two test repetitions; b) Only the brake specific metric (mg/kWh, g/kWh or #/kWh) has been used. Similar conclusions could be drawn when distance specific emission factors are examined; c) The Diesel vehicle is the reference when relative percentage data is presented.

The main findings of the investigation can be summarized to the following:

- A high correlation between the concentration in ppm measured by the gas PEMS analyser and by the laboratory analysers was found for all pollutants (e.g. NO_X linear correlation on average within 1% for Diesel and around 7% for CNG truck. Better values were recorded for the other contaminants: the emissions differences of CO, HC vehicle were generally very low and, in particular CO, close to the detection limit of the instruments; for PN the difference was also within a reasonable range). In the Diesel vehicle, the exhaust flow meter (EFM) of PEMS is around 4% lower than the estimated flow by the dilution tunnel (total diluted flow minus dilution air flow). Instead the outcomes obtained for CNG were not on the same wavelength: differences up to 40-50% have been detected, supposedly due to the presence of a high content of condensable water vapour in the exhaust gases (with peaks of 23.5%). The nature of the two fuels, as well as in the presence of after-treatment devices with opposite characteristics (highly hydrophilic the SCR unlike the TWC), could give a valid technical motivation of this behaviour. According to our findings a correction of the exhaust mass flow would seem recommendable. Anyway, in this report, we have presented the results without taking into account any correction of the flow nor for Diesel neither for CNG vehicle. The choice to show the real measured data without any compensation was conservative, as we preferred to take the risk to underestimate the emission factor values rather than overestimate them. As results, the overall assessment of the gas PEMS with the laboratory analysers gave differences of up to 50 mg/kWh for NO_X for the Diesel vehicle and up to 250 mg/kWh for CNG vehicle. However, the results were corrected for zero drift (approximately 50–100 mg/kWh), something permitted in the heavy-duty regulation, but not in the light-duty one. The FTIR and the tailpipe analysers had similar or slightly higher differences when compared to laboratory analysers. It should be mentioned that the diluted values were corrected for the background levels.

- For Diesel vehicle, real-world THC emissions were inside the proposed limits (both TA and ROAD) for all cycles. CNG ones were altogether higher in absolute terms (ISC_LIKE: Diesel 0.49 mg/kWh vs CNG 171.49 mg/kWh; CITY_SIM: Diesel 7.42 mg/kWh vs CNG 317.27 mg/kWh) anyway abundantly within the proposed limits. In CITY_MILAN calculated emission factors were two orders of magnitude lower in Diesel engine (0.79 mg/kWh) than in CNG (73.5 mg/kWh). The highest THC emissions of both vehicles were observed under cold start and low speed conditions. It necessary to clarify that the HC limits are different, since the regulation prescribed diverse limits in case the engine is CI (Compression Ignition, namely Diesel) or SI (Spark Ignition, as Gasoline or CNG in our case). Respectively a total limit of 0.16 g/kWh in CI engine and a double partial limit of 0.5 g/kWh for the Methane compounds and 0.16 g/kWh for the Non-Methane compounds in SI engines. As in a CNG vehicle, the hydrocarbon emitted at the tail pipe are principally Methane (>95-98%), we assumed that, for this vehicle typology, there was only a total limit coinciding with the Methane limit (0.5 g/kWh). This limit resulted indirectly much more severe than the regulated one, since we did not subtract the Non-Methane fraction from the total amount.

- CO emissions of both tested vehicles appear to be at very low levels, largely below the reference limits (4000 mg/kWh), indicating high overall effectiveness of the applied reduction technologies. In the metropolitan cycle (CITY_MILAN) CNG truck has a reduction of -87% compared to the Diesel one, with respectively 40.9 and 320.3 mg/kWh. This trend did not vary significantly among the different routes (around -71/-85% in the other cycles).

- NO_X aggregate emissions trend was contradictory: only in ISC_LIKE complete cycle, the Diesel vehicle presented higher value than the CNG (Diesel 199.22 g/kWh vs CNG 82.53 g/kWh), with a percentage decreasing of around -59% in favour of CNG vehicle. Instead, in the city conditions, namely in CITY_SIM and CITY_MILAN cycles, we observed a huge increase, in particular in the latter cycle. This circumstance is explainable with the important weight of the motorway part in the ISC_LIKE, in which the higher exhaust temperatures permitted to the after-treatment systems in the CNG truck (TWC) to have excellent results in terms of NO_X breakdown. Opposite results were found in the urban phases of all cycles, where the SCR can work with a lower temperature (>200°C) if compared with the TWC light-off temperature and the TWC Effective Conversion Temperature (ECT, defined as the temperature at which the NO_X reduction is practically complete). While Diesel tested vehicle respected the Euro VI certification limits in all cases, in "Urban" routes, CNG truck showed NO_X emission factor nearly 4 times higher than the Diesel (755.31 mg/kWh vs 157.1 mg/kWh), exceeding the adopted reference limits. A comparison with the emissions of other Diesel refuse trucks reported in the literature showed that the tested vehicle is one of the lowest emitting vehicles (600-700 mg/km vs. reported range of 400–1200 mg/km using a distance metric).

- Regarding PN, Diesel vehicle seemed not to be of concern due to the effectiveness of the currently available DPF systems (registered values at least one order of magnitude lower than the current laboratory type approval limit - TA), while in CNG vehicle, PN was within the reference TA limit only in the CITY_MILAN and in the CITY_SIM cycles (respectively 7.19×10^{10} and 5.45×10^{11}), not in the ISC_LIKE routes, in which slightly exceeded the proposed limit (7.73×10^{11}), nevertheless in any cases the ROAD limits has never been overcome. The CNG engine PN levels were 3 times higher than in Diesel one. Including also the regeneration events in the Diesel vehicle, the emissions increased the PN significantly, but it still remained below the limit of 6×10^{11} particle/kWh.

- Although in ISC_LIKE and in CITY_SIM the total CO_2 emitted in the complete cycle is higher in Diesel vehicle than in CNG truck (respectively -11 and -26% in the above mentioned routes), in CITY_MILAN the trend is opposite (+33%). Analyzing the CO_2 values broken down into speed bins and considering only the urban phases, in Diesel vehicle the variation in urban routes (ranged from 618.6 to 675.9 g/kWh), between different cycles, seemed to be insignificant, while for the CNG they had a big impact: they varied from 694.4 to 845.4 g/kWh (around 22%). The difference registered in CO_2 emissions factor is in opposite direction to the one found in the literature, in fact we expected lower CO_2 aggregate emission level in CNG truck rather than in Diesel vehicle also in "Urban" parts. Considering that in ISC_LIKE and CITY_SIM tests no compaction activity was requested, in CITY_MILAN the difference in the CO_2 values can be attributed to the increasingly power required by the CNG hydraulic pumps rather than to the Diesel ones to compress against the moving wall as the quantity of waste is gradually introduced into the container. In general, for both means, more garbage was introduced, higher was the resistance for the accessories, which needed more power by the engine.
- Diesel NH_3 emissions (the average around 6.9 ppm in ISC_LIKE and 3.1 ppm in CITY_SIM) were even lower than the laboratory Euro VI type-approval limit of 10 ppm, while the CNG were on the border line (the average around 10.1 ppm in ISC_LIKE and 3.6 ppm in CITY_SIM). The Ammonia is emitted due to the presence of a SCR converter, present only in Diesel truck, whilst in the CNG is produced by the fuel chemical nature (Methane).
- The Nitrous oxide (N_2O) emissions were significantly higher in the Diesel engine. They ranged on average from 46.9 (ISC_LIKE with regeneration) to 52.9 g/kWh (CITY_SIM). The CNG emitted 11.6 g/kWh in the ISC_LIKE and 12.4 in the CITY_SIM routes.
- ISC_COMPLIANT versus ISC_LIKE: the percentage deviations between the two procedures were within a reasonable difference. Assuming the ISC_COMPLIANT as the reference cycle, they approximately varied from -3 to 19% in Diesel vehicle and from -8 to 7% in CNG truck. More in detail, NO_X, that is considered the most critical, ranged from +6% in CNG vehicle to +11% in Diesel vehicle. Only THC in Diesel vehicle denoted a high impact: this was mainly due to the low values involved in Diesel THC emission factors. The results were reliable as, in perspective of the repeatability, the Coefficient of Variation (COV) was within a suitable range.
- The impact of lower starting coolant temperatures - and, in general, of the ambient temperature- before starting the engine (cold start) was rather important: a big increase in the PN level as well as a huge NO_X rise were registered respectively for Diesel and for CNG engines.
- The tightening of regulations and the implementation of stringent exhaust gas emission limit, represented a strong push to introduce new after-treatment devices and strategies. A substantial improvements achieved by switching from the older regulation (Euro V-EEV) to the new one (Euro VI) with a reduction in a range of 75-100% for the regulated pollutants in both technologies (Diesel and CNG).

Focusing our attention in particular on the real metropolitan cycle (CITY_MILAN), many aspects had a relevant weight and effect in the above-mentioned results. To better understand the testing results under severe operating conditions (made by frequent starts and stops, numerous accelerations, decelerations and idling for short intervals) it is essential to take into account different factors.

During "Urban" phases of the tests, both vehicles largely operated a low average speeds (around 7km/h) due to its typical operation of refuse collection, in which the vehicle is usually stationary for a long time during loading, so the exhaust gas temperature had a lot of oscillation around the light-off and ECT threshold of the after-treatment devices. The reason of some strange behaviours in the emission factors in the tested vehicles, e.g. NO_X, is to be found in the performances of the catalyst converter, due to the different ECT and light-off temperatures, and in the different thermal inertia of the converters, mainly owing to their different dimension, mass and materials composition as supports/substrates (e.g. wash-coated monolith).

Mainly, the SCR temperature was higher than the ECT threshold for more time (93.08%) in the whole "urban" cycles if compared with the ECT activation temperature of the TWC converter (only in 75.66% of the testing time). On the other hand, in the CNG truck, the TWC ECT (as well the respective light-off) temperature could be very sensible to an eventual variation of air-fuel ratio from the stoichiometric value, supposedly caused by a potential inadequate functioning of the auxiliaries during extra power demand. Maybe this fact, together with different inertial characteristics of the after-treatment devices, could contribute to have hypothetical warm-up periods (necessary to rise over the ETC threshold) longer than expected after the engine cooling down during city operations (high percentage of idling). Considering also a lower ambient temperature -on average lower of 4°C for CNG truck- before starting the engine (cold start), all these circumstances negatively impinged on the CNG vehicle.

The contribution of cold-start period was determining in the overall results. In fact, the cold-start period (weighted respectively 79.6% and 63.8% in NO_X emissions for Diesel and CNG) as well as the engine and the after-treatment device not perfect fully stabilized due to the poor mileage of the CNG vehicle (less than 3000km – CNG vehicle was brand new) played a decisive role in the observation of higher emissions (mainly NO_X) in CNG rather than in Diesel engine.

Furthermore, the CO_2 increase in the CNG vehicle during the "Urban" phase of metropolitan cycles (approximately +22% if compared with other 'Urban" routes, where no real compacting operations were requested), is an indirect validation of the hypothesis of a non-optimal setting of the hydraulic pumps that moved the accessories in the CNG truck, as it is rather counter-current with what is found in the literature on natural gas engines. Maybe another setting of the CNG vehicle might bring the numbers to the expected range.

Broadly, the pollutant emissions factors of the tested Diesel vehicle were better than its homologous CNG vehicle. These results are in agreement with the finds of some recent studies [**1**] that indicate that the current notion that natural gas engines are cleaner than diesel might not be valid any longer. However, the JRC would like to stress that this general conclusion is only applicable to the vehicles and the conditions tested in this experimental project and that under no circumstances it can be generalised to other vehicles or fleets. Although the results of this study cannot be extended to other vehicles, they show that Euro VI Diesel vehicles can still be suitably used as refuse collection vehicles, since the comparison with the emissions of other diesel refuse trucks reported in the literature exhibited that it is one of the lowest emitting vehicles.

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List of abbreviations and definitions

A/F	Air Fuel Ratio
AMSA	Azienda Milanese Servizi Ambientali
ASC	Ammonia Slip Catalyst
CF	Conformity Factor
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2AW	CO_2 based Average Window
DG GROW	Directorate General Internal Market, Industry, Entrepreneurship and SMEs
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
EC	European Commission
ECU	Electronic Control Unit
EEA	European Environmental Agency
EF	Emission Factor
EFM	Exhaust Flow Meter
EGR	Exhaust Gas Recirculation
EU	European Union
FID	Flame Ionization Detector
FTIR	Fourier-Transform InfraRed spectroscopy
GHG	Greenhouse Gas
GPS	Global Positioning System
HD/HDVs	Heavy-Duty/Heavy-Duty Vehicles
ISC	In-Service Conformity (Programme)
JRC	Joint Research Centre
MAW	Moving Average Window
NDIR	Non-Dispersive infraRed
NDIR	Non-Dispersive Infrared Sensor

NDUV	Non-Dispersive UltraViolet
NMHC	Non-Methane Hydrocarbons
NO/NO_2	Nitric oxide (nitrogen monoxide)/Nitrogen dioxide
NOx	Oxides of Nitrogen
NPET	NanoParticle Emission Tester
FID	Flame Ionization Detector
OBD	On-Board Diagnostic System
OEMs	Original Equipment Manufacturer
PEMS	Portable Emission Measurement System
PN	Particle Number
SCR	Selective Catalytic Reduction
SEMS	Smart Emissions Measurement Systems
THC	Total HydroCarbons, also referred to as HC
VELA	Vehicle Emission LAboratory
WAW	Work based Average Window

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Annex 1. Euro VI heavy-duty engine emission limits at Type Approval (Homologation Test)

Table 19. EU emission standards for heavy-duty CI (Diesel) and PI engine: Transient testing.

	Euro VI Limit values							
	CO (mg/kWh)	THC (mg/kWh)	NMHC (mg/kWh)	CH_4 (mg/kWh)	NO_X (1) (mg/kWh)	NH_3 (ppm)	PM mass (mg/kWh)	PN number (#/kWh)
WHSC (CI)	1500	130			400	10	10	8.0×10^{11}
WHTC (CI)	**4000**	**160**			**460**	**10**	**10**	$\mathbf{6.0 \times 10^{11}}$
WHTC (PI)	**4000**		**160**	**500**	**460**	**10**	**10**	(2) $\mathbf{6.0 \times 10^{11}}$

PI = Positive Ignition
CI = Compression Ignition
(1) The admissible level of NO_2 component in NO_2 limit value may be defined at a later stage
(2) The limit value shall apply as from the dates set out in row B of Table 1 of Appendix 9 of Annex I to Regulation (EU) No 582/2011.'

Source: ANNEX XV Reg(EU) 582/2011 – amendment 2019-12-15

Annex 2. Euro VI

1 Test Cycles

The European emission limit values being established under both the World Harmonized Stationary Cycle (WHSC) and the World Harmonized Transient Cycle (WHTC).

For certification of heavy-duty vehicle emissions, engines are tested on a test bed and emissions are reported as g/kWh. The WHSC is a steady-state cycle also based on a weighted sum of emissions over thirteen modes, which are combinations of engine speed and load. The cycle is based on real-world drives in Europe, the United States, Japan, and Australia. It is a hot-start cycle following preconditioning at an engine speed of 55% and 50% load. The WHTC test is a transient engine test of 1800 seconds, with several motoring segments, originally developed by the UNECE Working Party on Pollution and Energy. It is based on the worldwide pattern of real-world heavy commercial vehicle use based on typical driving conditions found in Europe, the United States, Japan, and Australia.

2 Durability and In-Service emissions

To ensure the tailpipe emissions are effectively limited throughout the normal life of the vehicle, under normal conditions of use, tests to ensure the durability of pollution control devices and in-service conformity should be carried out by manufacturers at the mileage and time periods shown below in **Table 20**.

Table 20. Emission durability period.

Vehicle Category (1)	Period (2)	
	Euro IV-V	Euro VI
N1 and M2	100 000 km / 5 years	160 000 km / 5 years
N2 N3 ≤ 16 ton M3 Class I, Class II, Class A and Class B ≤ 7.5 ton	200 000 km / 6 years	300 000 km / 6 years
N3 > 16 ton M3 Class III and Class B > 7.5 ton	500 000 km / 6 years	700 000 km / 6 years

(1)Mass designation (in metric tons) are "maximum technically permissible mass"

(2) km or year period, whichever is the sooner

Source: Source: JRC Vela, 2020

3 Real-World Emissions

Heavy-duty vehicles have historically not achieved the real-world NO_X emissions expected under Euro V and previous standards. In-service emissions for heavy-duty vehicles were initially addressed in Regulation 595/2009, and subsequently adopted in Regulation 582/2011 [**7**]. The Euro VI regulation set out the requirements for checking and demonstrating the conformity of in-service engines and vehicles using PEMS. Additional measures, such as the shift to world harmonized test cycles for stationary and transient testing, and the inclusion of cold-start testing, have greatly improved the certification test and its ability to guarantee real-world achievement of the Euro VI emission limits.

Annex 3. Most important Euro VI In-Service Conformity (ISC) requirements

This annex summarizes the Euro VI in-service conformity (ISC) requirements. According to the moving average (MAW) method, the pollutant emissions are integrated over windows which reach the reference engine work or CO_2 mass emissions of the specific engine in the engine dynamometer type approval test (WHTC). The calculation is then repeated for each second. The requirements are summarized in **Table 21**. EMROAD is a calculation tool that can be used to analyse the data.

Table 21. Most important Euro VI in-service conformity (ISC) requirements (heavy-duty vehicle N3 category).

Euro VI (ISC)	Step A-C	Step D – E
Regulation	582/2011 [**7**]	2016/1718 [**8**], 2018/932 [**9**]
Duration	5×WHTC	4-7×WHTC
Payload	50-60%	10-100%
Definition U, R, M	Speed <50, 50-75, >75 km/h	Map or first acceleration
Time shares U, R, M (N3)	20%, 25%, 55%	30%, 25%, 45%
Mean speeds U, R, M (N3)	-	15-30, 45-70, >70 km/h
Order	U → R → M (recommended)	U → R → M
Cold start inclusion	No	No/SI (only Step E)
Starting $T_{coolant}$	any	<30°C
Evaluation starts at	$T_{coolant}$>70°C	$T_{coolant}$>70°C
Evaluation method	MAW (see Annex 5)	MAW (see Annex 5)
MAW power threshold	>20%	>10%
Cumulative percentile MAW	90%	90%

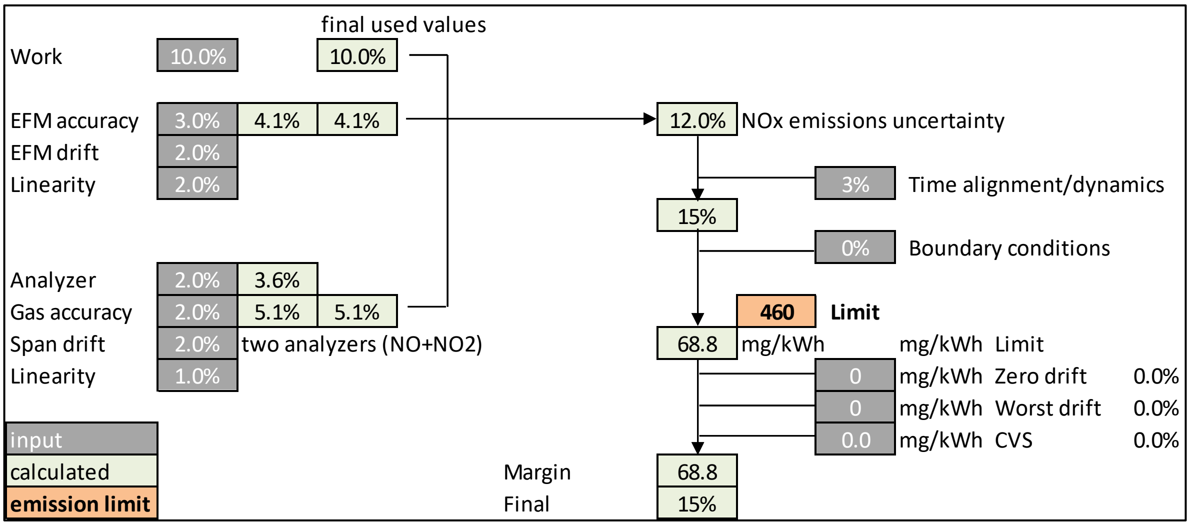
WHTC=World harmonized U=Urban; R=Rural; M=Motorway; MAW=Moving average window

Source: JRC Vela, 2019

Annex 4. PEMS measurement uncertainty for heavy-duty vehicles

This annex gives the PEMS uncertainty of heavy-duty vehicles based on the analysis that was conducted for light-duty vehicles [**35**]. The uncertainty values were taken from the regulation requirements regarding accuracy, linearity etc. No drift uncertainty was considered because drift correction was applied in our results. The final theoretical uncertainty of 68.8 mg/kWh (15%) (see **Figure 67**) is in line with the one found experimentally for the Diesel vehicle (see **Figure 20**) not for the CNG one (see **Figure 21**).

Figure 67. PEMS measurement uncertainty for heavy-duty vehicles (NO_X case).



Source: JRC Vela, 2019

Annex 5. Emission Evaluation Methods for ISC

1 Introduction

According to the amended version of the Regulation (EU) No 582/2011 [**7**], the conformity of in-service vehicles or engines of an engine family shall be demonstrated by testing vehicles on the road operated over their normal driving patterns, conditions and payloads. The in-service conformity test shall be representative for vehicles operated on their real driving routes, with their normal payload and with the usual professional driver of the vehicle. When the vehicle is operated by a driver other than the usual professional driver of the particular vehicle, the alternative driver shall be skilled and trained to operate vehicles of the category subject to be tested.';

In-service conformity testing represents one of the building blocks of the type-approval procedure and allows for the verification of the performance of emission control systems during the useful lifetime of vehicles. In accordance with Commission Regulation (EU) No 582/2011 [**7**], the tests are performed by means of portable emission measurement systems (PEMS) which assess the emissions in the normal operations of use. The PEMS approach is equally applied to verify off-cycle emissions during the type-approval certification.

The data analysis method, the so-called "averaging window methods", was considered as a baseline method.

2 Moving Averaging Window (MAW) method

The averaging window method is a moving averaging process, based on a reference quantity obtained from the engine characteristics and its performance on the type approval transient cycle. The reference quantity sets the characteristics of the averaging process (i.e. the duration of the windows). Using the MAW method, the emissions are integrated over windows while the power is averaged in the windows whose common characteristic is the reference engine work or CO_2 mass emissions. The reference quantity is easy to calculate or (better) to measure at type approval:

- In the case of work: the reference work is the one obtained in the certification test cycle.
- In the case of the CO_2 mass: from the engine CO_2 emissions on its certification cycle.

Using the engine work or CO_2 mass over a fixed cycle as reference quantity is an essential feature of the method, leading to the same level of averaging and range of results for various engines. Time based averaging (i.e. windows of constant duration) could lead to varying levels of averaging for two different engines.

The first window is obtained between the first data point and the data point for which the reference quantity (1 x CO_2 or work achieved at the regulatory cycle) is reached. The calculating window is then moved, with a time increment equal to the data sampling frequency (at least 1Hz for the gaseous emissions).

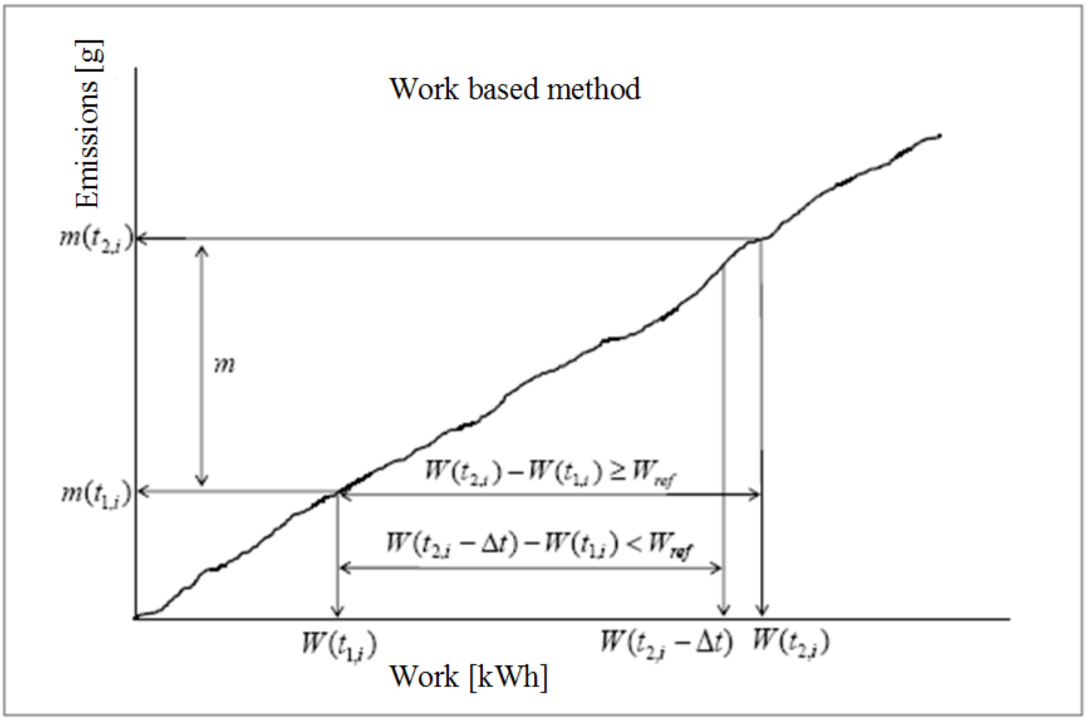
The following sections are not considered for the calculation of the reference quantity and the emissions of the averaging window due to invalidated data originated from:

- The periodic verification of the instruments and/or after the zero drift verifications;
- The data outside the applicable conditions (e.g. altitude or cold engine).

For the sake of completion, in the following section we recall the details of the calculation methods.

2.1 Work based method

Figure 68. Work based method.



Source: JRC Vela, 2018

The duration $(t_{2,i} - t_{1,i})$ of the i[th] averaging window is determined by:

$W(t_{2,i}) - W(t_{1,i}) \geq W_{ref}$

Where:

– $W(t_{j,i})$ is the engine work measured between the start and time $t_{j,i}$, [kWh];

– W_{ref} is the engine work for the homologation cycle, [kWh].

– $t_{2,i}$ shall be selected such that:

$$W(t_{2,i} - \Delta t) - W(t_{1,i}) < W_{ref} \leq W(t_{2,i}) - W(t_{1,i})$$

where Δt is the data sampling period, equal to 1 second or less.

2.1.1 Calculations of the brake specific gaseous pollutant emissions

The brake specific gaseous pollutant emissions e_{gas} [g/kWh] shall be calculated for each averaging window and each gaseous pollutant in the following way:

$$e_{gas} = \frac{m}{W(t_{2,i}) - W(t_{1,i})}$$

Where:

– m is the mass emission of the gaseous pollutant, mg/averaging window

– $W(t_{2,i}) - W(t_{1,i})$ is the engine work during the i[th] averaging window, [kWh]

2.1.2 Selection of valid averaging windows

The valid averaging windows are the averaging windows whose average power exceeds the power threshold of 20 % of the maximum net engine power. The percentage of valid averaging windows shall be equal or greater than 50 %.

The test shall be considered void if the percentage of valid averaging windows is less than 50 %.

2.1.3 Calculations of the conformity factors

The conformity factors shall be calculated for each individual valid averaging window and each individual gaseous pollutant in the following way:

$$CF = \frac{e}{L}$$

Where:

– e is the brake-specific emission of the gaseous pollutant, [g/kWh];

– L is the applicable limit, [g/kWh].

3 Calculation steps

To calculate the conformity factors, the following steps have to be followed:

- Step 1: (If necessary) Additional and empirical time-alignment.
- Step 2: Invalid data: Exclusion of data points not meeting the applicable ambient and altitude conditions: for the pilot program, these conditions (on engine coolant temperature, altitude and ambient temperature) were defined in the Regulation [R1]. Definition of valid and invalid event as explained above.
- Step 3: Moving and averaging window calculation, excluding the invalid data. If the reference quantity is not reached, the averaging process restarts after a section with invalid data.
- Step 4: Invalid windows: Exclusion of windows whose power is below 20% of maximum engine power.
- Step 5: Calculation of the CF for each of the valid windows.
- Step 6: Selection of the reference CF value from all the valid windows: i.e. 90th cumulative percentile.

Steps 2 to 6 apply to all regulated gaseous pollutants.

4 Actual situation and considerations

Under current regulatory requirements (until step C) [**7**] only emission windows of mean power >20% of the maximum engine power are evaluated. An amendment to this regulation [**5**], called step D, which entered into force from September 2018 for new types (September 2019 for all new vehicles), reduced the threshold to 10% and changed the time shares to 25% (urban), 30% (rural) and 45% (motorway) [**6**]. Another amendment (step E) in the future is planned to include particle number testing and cold start in the evaluation. Thus, for the same trip and vehicle, the final emissions results can be different depending on the regulatory step and the evaluation method [**10**].

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