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Assessment of the Heavy-Duty Natural Gas technology

Theodoros Grigoratos, Georgios Fontaras,
Barouch Giechaskiel and Giorgio Martini

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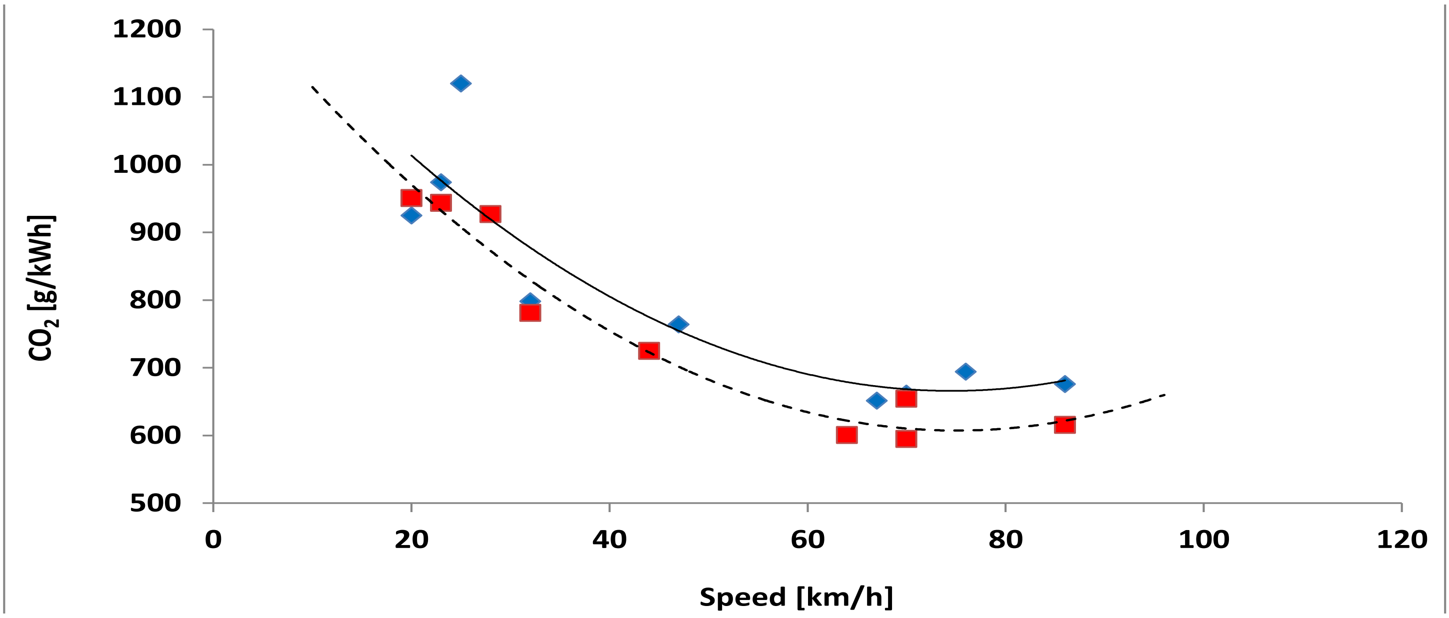

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Joint Research Centre
Institute for Energy and Transport

Contact information
Giorgio Martini
Address: Joint Research Centre, Via Enrico Fermi 2749, 21027 Ispra (VA), Italy
E-mail: giorgio.martini@jrc.ec.europa.eu
Tel.: +39 0332 78 9293
Fax: +39 0332 78 5236

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Abstract

Heavy Duty Vehicles (HDV) powered by Compressed Natural Gas (CNG) are seen as a possible option for curbing CO_2 emissions, fuel consumption and operating costs of goods transport. CNG engines have been employed in public use HDVs as an alternative to diesel engines due to their environmental benefits, and particularly due to lower particulate matter (PM) and nitrogen oxides (NO_x) emissions. In the framework of the current project, an advanced newly designed CNG prototype engine developed as part of the 7th Framework Programme research project "CO_2 Reduction for long distance transport" (CO_2RE), is benchmarked against its parent Euro V compliant CNG engine (reference) in order to quantify the improvement in terms of real-world emissions. Results indicated a significant reduction in CO_2 emissions with the prototype CNG engine both at low and high loads, which varied between 5.0-8.4%. The highest CO_2 reduction was observed during on-road testing, with the corresponding reduction at low loads being more pronounced compared to high loads. Furthermore, reductions of NO_x and CO emissions were observed under all testing conditions. On the other hand, hydrocarbon and methane emissions were increased with the introduction of the Prototype engine.

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EXECUTIVE SUMMARY

Heavy Duty Vehicles (HDV) powered by Compressed Natural Gas (CNG) are seen as a possible option for curbing CO_2 emissions, fuel consumption and operating costs of goods transport. CNG engines have been employed in public use HDVs (i.e. transit and school buses, garbage collection trucks) as an alternative to diesel engines due to their environmental benefits, and particularly due to lower particulate matter (PM) and nitrogen oxides (NO_x) emissions. Furthermore, CNG engines are preferred due to their cost benefits as natural gas has been clearly cheaper than diesel in many countries, as well as for political reasons such as the high public visibility and acceptance of such measures. In the framework of the current project, an advanced newly designed CNG prototype engine, which was developed as part of the 7th Framework Programme research project **"CO_2 Reduction for long distance transport"** (CO_2RE), is benchmarked against its parent Euro V compliant CNG engine (reference) in order to quantify the improvement in terms of real-world emissions. A detailed series of tests have been performed with the new engine configuration in comparison to a similar series of tests done with the CNG existing architecture (throttled engine). Both engines were installed on the same demonstrator truck, which was later tested under different cycles and operating conditions. In order to assess the benefit in terms of emissions, the demonstrator truck equipped with the reference engine was tested at the beginning of the project to define the benchmark values against which comparisons were later made. The newly developed engine was optimized for urban emission profiles and operation such as garbage collection purposes. The main technological innovation involves a new cylinder head equipped with a variable valve actuation (VVA) system designed to provide on the intake side a continuous fully flexible variation of the valve lift and timing. Following the development and calibration process, the prototype engine coupled with the identical exhaust aftertreatment system of the reference engine and a new engine control unit, were installed on the truck and the test protocol was repeated. Tests included HDV chassis dyno measurements under various driving conditions, as well as on-road tests with the Portable Emissions Measurement System (PEMS). Regulated pollutant emissions were measured including CO_2, CO, THC, CH_4, and NO_x. Results indicated a significant reduction in CO_2 emissions with the prototype CNG engine both at low and high loads, which varied between 5.0-8.4%. The highest CO_2 reduction was observed during on-road testing, with the corresponding reduction at low loads being more pronounced compared to high loads. Furthermore, reductions of NO_x and CO emissions were observed under all testing conditions. On the other hand, hydrocarbon and methane emissions were increased with the introduction of the prototype engine.

ABBREVATIONS AND ACCRONYMS

A/F	Air Fuel Ratio
BSFC	Brake Specific Fuel Consumption
CNG	Compressed Natural Gas
CLD	ChemiLuminescence Analyzer
CNG	Compressed Natural Gas
CVS	Constant Volume Sampler
ECU	Electronic Control Unit
EEV	Enhanced Environmentally-friendly Vehicles
EGR	Exhaust Gas Recirculation
EIVC	Early Intake Valve Closing
ETC	European Transient Cycle
GHG	Green-House Gas
GPS	Global Positioning System
HDV	Heavy Duty Vehicles
HEPA	High Efficiency Particulate Air filter
HFID	Heated Flame Ionization Detector
LIVO	Late Intake Valve Opening
LNG	Liquid Natural Gas
LPG	Liquid Petroleum Gas
NDIR	Non-Dispersive Infra-Red
NDUV	Non-Dispersive Ultra-Violet
NG	Natural Gas
OBD	On Board Diagnosis
PEMS	Portable Emission Measurement System
PM	Particulate Matter
PN	Particle Number
RPM	Engine Speed
THC	Total Hydrocarbon
TWC	Three Way Catalyst
VVA	Variable Valve Actuator
WHTC	World Harmonized Transient Cycle
WHVC	World Harmonized Vehicle Cycle

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1. INTRODUCTION

In view of rapidly growing energy demands, increasing public concern regarding greenhouse gas (GHG) emissions, as well as the introduction of more stringent regulation regarding gaseous and particle emissions (EURO VI standard limits of NO_x, CH_4, and PM are about 75%, 55%, and 67%, lower compared to the corresponding EURO V limits), HDV manufacturers and operators are willing to further invest in fuel and emissions reduction technologies. Apart from new and technologically advanced vehicles and powertrains the improvement of fuel efficiency and environmental performance of existing trucks and buses is being investigated. Gas fueled vehicles, powered by CNG are considered to be an overall sustainable option for curbing CO_2 emissions and fuel consumption from HDVs.

Gas fueled HDVs are already available in the market since several years [1]. In general, CNG engines have been employed in public use heavy-duty vehicles (i.e. buses, garbage collection trucks) as an alternative to diesel engines mainly due to their environmental benefits, and particularly due to their lower particulate matter (PM), particulate number (PN) and nitrogen oxides (NO_x) emissions. Furthermore, energy specific CO_2 emissions are mentioned to be lower for CNG than for diesel due to high H/C ratio, unless CO_2 equivalent emissions (i.e. tail-pipe CO_2 plus the emissions of CH_4 multiplied by 25 for global warming potential) are examined. Even in this case CNG engines have an advantage over conventional diesel engines. Furthermore, CNG engines are preferred due to their cost benefits, as well as for political reasons such as the high public visibility and acceptance of such measures. According to Yoon et al. [2] the natural gas urban bus population (including compressed and liquefied natural gas) has more than doubled in the United States during the last decade, while in the state of California they have increased from 24% of the total bus fleet in 2001 to 45% in 2011 [3]. Other studies also report increasingly usage of new buses powered by CNG engines worldwide [4-6]. CNG trucks for garbage collection purposes have been extensively used in the US and in other countries worldwide for more than a decade [7-11].

The positive and negative aspects associated with the application of gaseous fuels in HDVs have been discussed extensively by various researchers [2-6, 12-15]. Transition from diesel to gaseous hydrocarbon fuels leads to remarkable reductions in NO_x and PM emissions, particularly for older vehicles. Although PM and NO_x emissions from the latest technology diesel engines equipped with traps are comparable to the corresponding emissions from CNG engines, the emissions from advanced CNG engines with three-way catalyst (TWC) are reported to be even lower [1-4]. On the other hand, some of the existing technologies using methane as fuel suffer from problems with methane slipping through the combustion process, as well as with the exhaust after-treatment system if no special devices are installed [12]. This problem is very common at dual fuel systems. Regarding fuel and energy efficiency the results depend greatly on the technology applied, the type of engine and the usage profile of the vehicle.

In this study, an advanced newly designed CNG prototype engine (hereafter also mentioned as Prototype engine) was benchmarked against its parent Euro V compliant CNG reference engine in terms of gaseous exhaust emissions namely NO_x, CO_2, CO, CH_4 and HC. The main technological innovation included a new cylinder head equipped with a variable valve actuator (VVA) system designed to provide a continuous fully flexible variation of the valve lift and timing to the intake side. The newly developed engine was optimized for urban emission profiles and operation such as garbage collection purposes. Tests were divided into stand-alone engine tests and vehicle tests. Vehicle tests consisted of chassis dynamometer measurements and on-road tests, which were conducted in order to verify real life emissions and compare the results with results from testing in the laboratory. The current study is a part of the 7th Framework Programme research project **“CO_2 Reduction for long distance transport”**.

2. EXPERIMENTAL

2.1. CONCEPT ENGINE DESCRIPTION

The concept is derived from the 7.8L CNG engine produced by Fiat PowerTrain Industrial (Figure 1). It is a four stroke engine operating under a homogeneous mixture of air and fuel ignited by a spark plug. The main engine specifications and performance characteristics are demonstrated in Table 1. This CNG engine takes its mechanical structure from the six cylinders in line Diesel version which has a displacement of 7.79 dm^3 and 4 valves per cylinder. The CNG cylinder head is specific with spark plug installation, integrated intake manifold, and fuel mixer. The combustion chamber is a pot type bowl in the piston with a reduced compression ratio of 11.5:1. The engine was initially developed to comply with EURO V / EEV targets. Emission control involves a closed loop lambda ($\lambda=1$) and a three-way catalyst (TWC).

Figure 1. CNG reference engine

Stoichiometric mixture is applied through the complete engine map. This is because the achievable temperature reduction with the rich mixture when using gasoline cannot be reached with CNG, while at the same time a lean mixture would affect the catalyst conversion efficiency on NO_x. In order to withstand the high temperatures which are typical of stoichiometric combustion, proper material have been selected for exhaust components (i.e. valves, valve seats, manifold and turbocharger housing), thus removing any kind of limitations towards full performance. It should be mentioned that the advanced closed loop control along with the TWC technology adopted for the emission control, prevent the use of add-on devices like secondary air and exhaust gas recirculation (EGR). The cooling system has also been improved in order to mitigate temperature of cylinder head. A dedicated electronic control unit (ECU) is necessary for managing all engine functions.

Table 1. CNG engine specifications and performance

Specifications	**Unit**	**Description**
Thermodynamic cycle		Otto 4 stroke
Air intake		TAA
Arrangement		6L
Bore *x* Stroke	*mm*	115 *x* 125
Total displacement	*L*	7.8
Valves per cylinder		4
Cooling system		liquid
Direction of rotation		CCW
Compression ratio		11:1
Injection system		Multi point
Performance		
Maximum rating [*]	*kW*	243
At speed	*rpm*	1785-2000
Maximum torque	*Nm*	1300
At speed	*rpm*	1200-1785
Max no load governed speed	*rpm*	2400
Minimum idling speed	*rpm*	600
Max starting T without auxiliaries	*°C*	-25
Dry weight	*kg*	800

Aftertreatment system

Stoichiometric ratio has been selected under all operating conditions in order to optimize emission control. A proper location of the TWC has been adopted to reach temperature threshold, thus enabling full device efficiency (> 98%) valid simultaneously for all gaseous pollutants. The light off temperature is achieved in a few seconds by means of a dedicated control strategy. The system is compliant with the extremes Natural Gas composition (GR gas: 87% CH_4 - 13% C_2H_6 / G25 gas: 86% CH_4 -14% N_2).

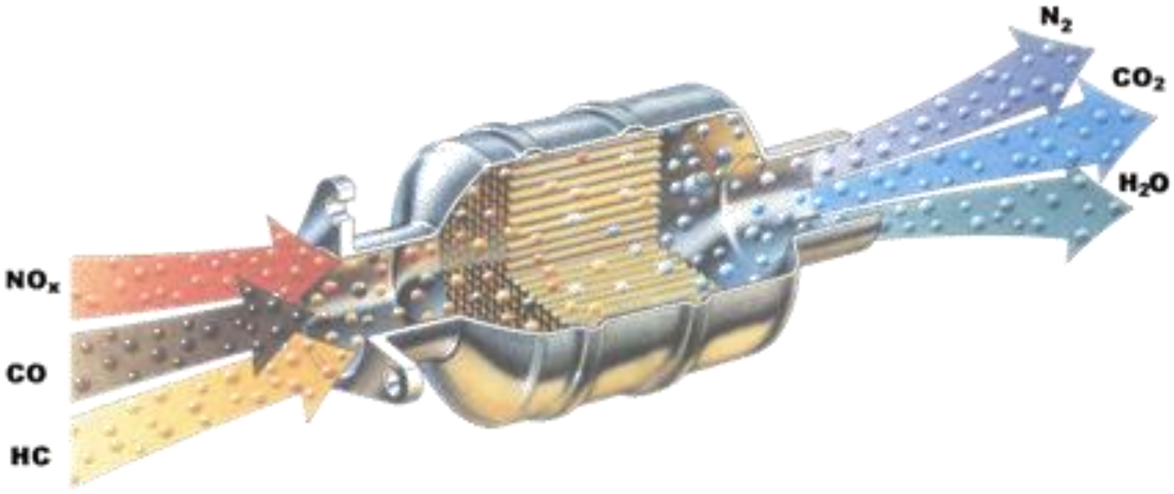


Figure 2. Three way catalyst

CO and NO_X have a lower light-off temperature (~ 250°C) than THC (~ 450°C), therefore in cold condition catalyst starts to convert CO and NO_X first. This principally depends on the chemical structure of fuel molecules and on the catalyst formulation. CH_4 is a very stable molecule and this justifies the high light-off temperature even if a dedicated catalyst Pd-based is adopted. In general, a spark advance retarding in combination with a slight air/fuel ratio enrichment (more fuel than stoichiometric value) could be used to enlighten the catalyst, however this strategy was not adopted in these tests due to the cycles adopted (ETC is a hot start cycle, WHVC was performed in hot condition and PEMS cold start phase was negligible compared to the total duration of the cycle).

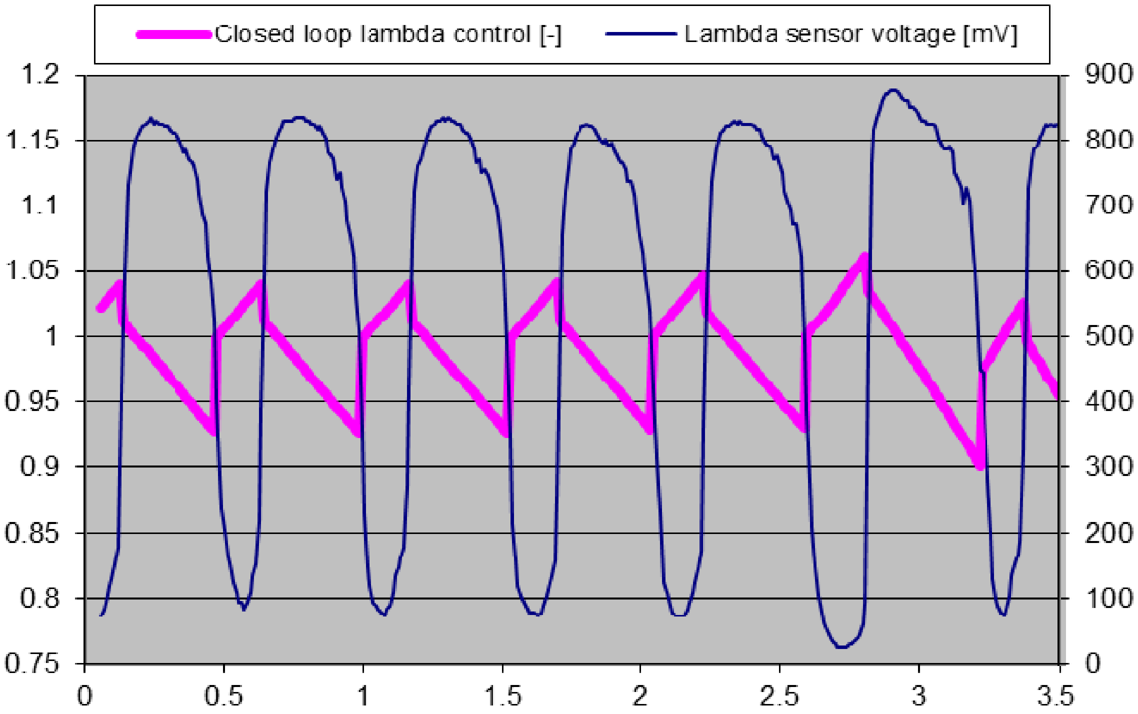


Figure 3. Typical behavior of the closed loop lambda control

The aftertreatment system is composed by a three-way type catalyst converter with a ceramic substrate and an external stainless steel muffler (Figure 2). The catalyst has 400 cells per square inch (62 per cm^2), 267 and 152.4 mm diameter and length, respectively. Stoichiometric mixture is obtained by continuously switching from slightly rich to slightly lean conditions. The switch increases the efficiency of the TWC in terms of performances since it makes sure that A/F value does not oscillate.

The closed loop lambda control (KO2) multiplicative factor is applied to calculate the CNG quantity to be injected. The type of the lambda sensor is “on-off”, and the main event affecting the KO2 factor is the lambda sensor output transition through the stoichiometric value. When this event is detected the first correction is of “proportional” step-wise type. After this step the correction follows a continuous ramp identified as “integral” type. Figure 3 shows the typical behavior of the closed loop lambda control.

The self-adaptive strategy is a function able to compensate for the long-term drifts that affect A/F ratio control and are caused by component aging and wear. Also this strategy operates in order to align the A/F ratio to the gas quality variations which is important for the CNG engine.

Fuel system

Fuel system components are specific of this engine: CNG pressure regulator heated with engine coolant fluid and shut-off valve integrated, flexible pipe from chassis to rail, fuel rail, and two electro-injectors for each cylinder. The Sequential Multi-Point Injection system is capable to tune the six pairs of injectors according to the intake sequence of each cylinder. Figure 4 shows a generalized example of the overall control system layout.

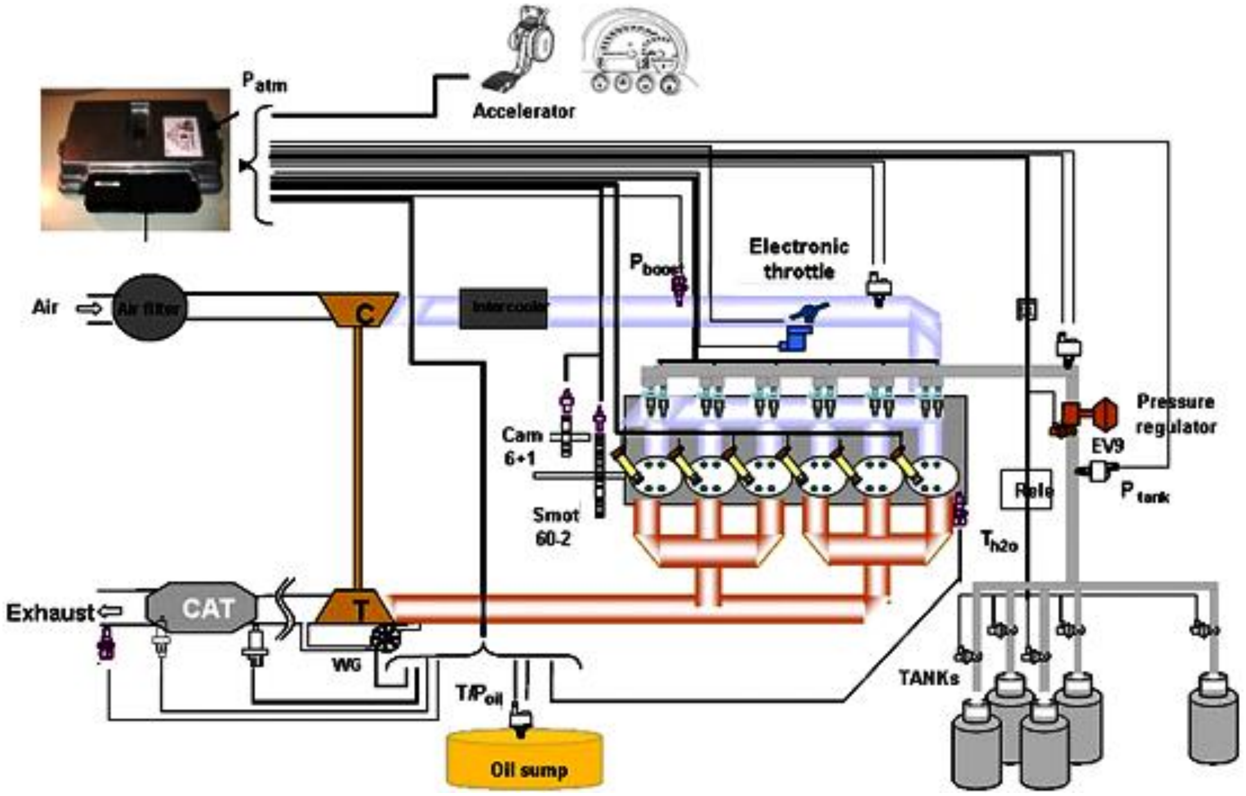


Figure 4. Control system layout

The injected quantity is metered by the ECU acting on the injector opening time. The engine control is based on the speed density system, which determines the injector opening time (t_j)

based on: the calculated air flow, the desired injection quantity according to stoichiometric air/fuel ratio, and the injector flow characteristic. The relevant sensors for air mass flow calculation are: pressure and temperature of CNG/air mixture in the intake manifold, engine speed, and coolant temperature. The relevant sensors for the injection time (t_j) calculation in order to provide the desired injection quantity are: pressure and temperature of CNG in the rail, as well as the battery voltage. The injection time calculation is mainly based on the rail pressure and temperature, thus the model defines the static flow rate - the dynamic behavior also considers the opening time as a function of the rail pressure and the battery voltage. The end of injection (phase of injection) is defined through a map function of engine speed and load.

Variable valve actuator

A specific projected cylinder head with a variable valve actuator (VVA) system has been installed on the base engine in order to verify the potential in terms of fuel consumption reduction. The VVA system application to CNG engine allows to tune the air flow quantity in combustion chamber using specific calibration strategies: EIVC (Early Intake Valve Closing, which means that intake valves are closed before the point defined by camshaft profile) or LIVO (Late Intake Valve Opening, which means that intake valves open after the mechanical point determined by camshaft profile) or, in addition, a combination of this two elementary tunings. As a consequence it is possible to use a torque level control based on intake valves opening phase flexible duration to avoid the throttle valve pressure drop. The reduction of inlet pressure drop would bring an increase in engine efficiency at partial loads due to pumping friction reduction in comparison with reference throttled engine, and a consequent reduction in engine consumption and in CO_2 emission level. Figure 5 shows a functional scheme and a diagram where the two main intake valves operating modes are described.

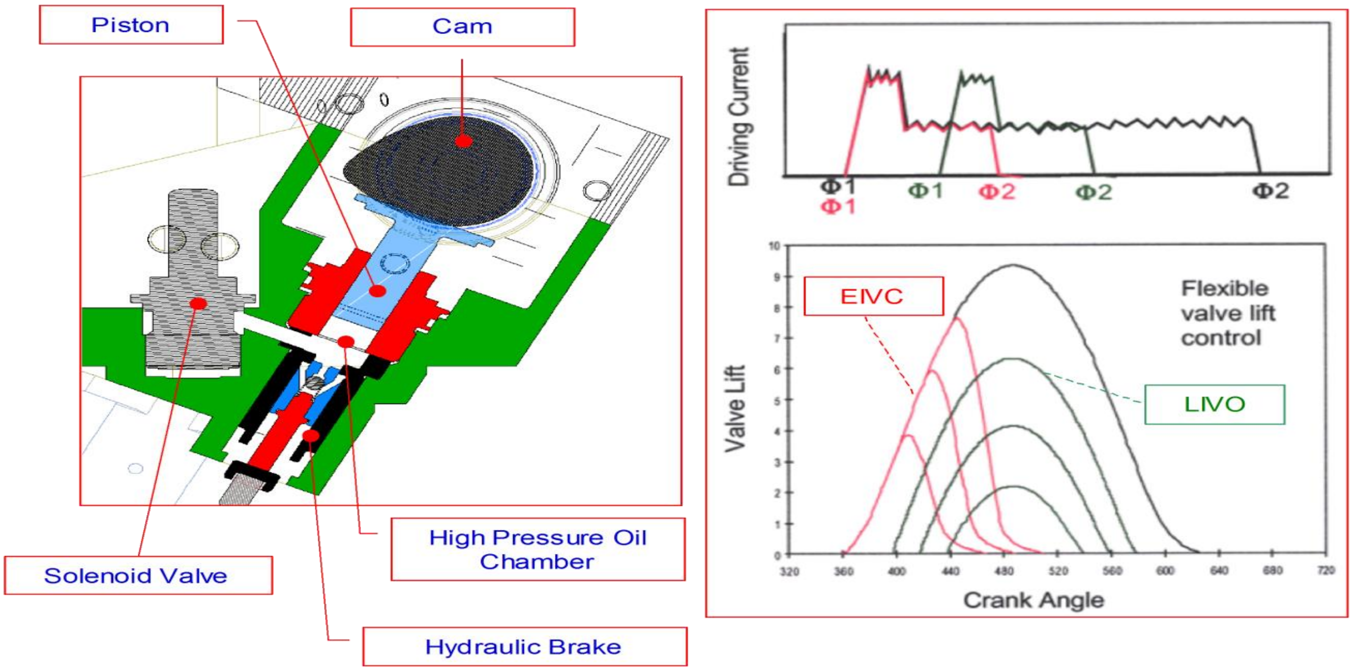


Figure 5. A functional scheme where the two main intake valves operating modes are described

Vehicle characteristics

The vehicle used in the study was an IVECO truck (model Stralis) with two axles and a manual transmission (Figure 6). The total mass (vehicle and load) was 12900 kg. Load was set at 50% of the maximum, meaning that the vehicle was set with additional ballast to simulate 50% of the total weight transportable as this is a requirement of the PEMS system.

Figure 6. Vehicle in VELA 7

2.2. DRIVING CYCLES AND TEST PROTOCOL

Chassis dyno measurements were performed over the World Harmonized Vehicle Cycle (WHVC), and an adapted European Transient Cycle (ETC). The speed vs time profiles of the adapted ETC and the WHVC are shown in Figure 7.

The European Transient Cycle (once also referred to as FIGE transient cycle) has been developed by the former FIGE Institute, Aachen, Germany, based on real road cycle measurements of heavy duty vehicles and had been introduced for emission certification of heavy-duty diesel engines in Europe starting in the year 2000 (Euro I to V). However, it has not been used for certification of entire vehicles. The adapted ETC cycle used for the purposes of the current study was derived taking into consideration the vehicle’s characteristics (road loads, mass) in order to replicate as closely as possible the engine operating points of the original test cycle. The cycle consists of three distinct operating phases namely: an urban phase lasting 600 seconds with average and maximum speed of 23 km/h and 50 km/h, respectively, a semi-urban phase lasting 600 seconds with average and maximum speed of 65 km/h and 80 km/h, respectively and a highway phase lasting 600 seconds with average and maximum speed of 86 km/h and 90 km/h, respectively.

The World Harmonized Vehicle Cycle is a cycle which can be used for testing entire vehicles on a chassis dynamometer. It is a not standardized chassis dyno test and is not used for regulatory purposes. In general, test procedures for chassis dynamometer are not identical to the procedures used for engine dynamometer testing. However, the results of WHVC can be used to compare the emission levels of a vehicle with the emission levels of an engine tested under the regulated World Harmonized Transient Cycle (WHTC). The WHVC consists also of three segments, representing urban, rural and motorway driving: the urban phase lasts 744 seconds with average and maximum speed of 20 km/h and 66 km/h, respectively, the semi-urban phase lasts 440 seconds with average and maximum speed of 32 km/h and 76 km/h, respectively and the highway phase lasts 615 seconds with average and maximum speed of 70 km/h and 88 km/h, respectively.

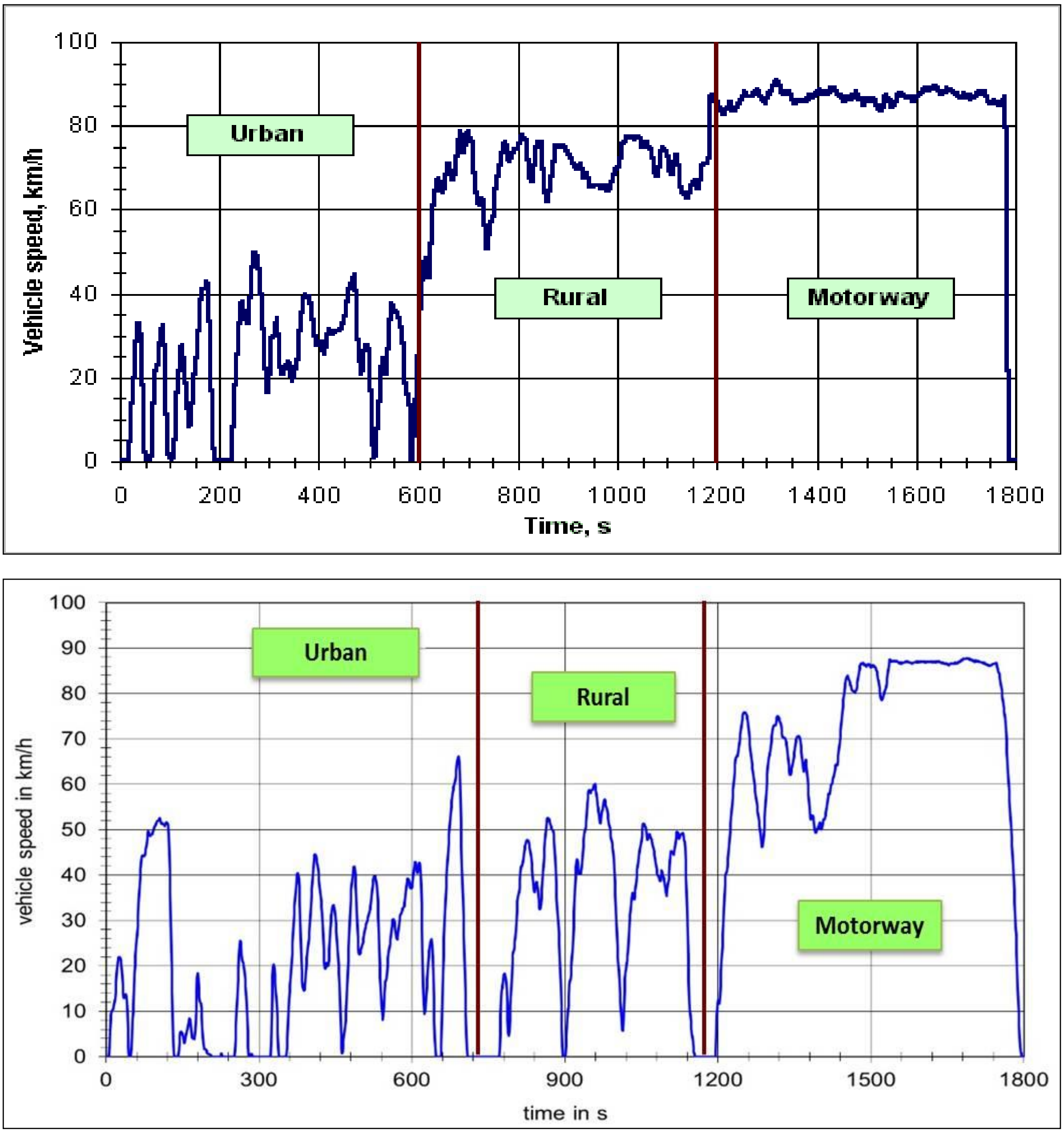


Figure 7. Speed vs time profile of ETC (Up) and WHVC (Down)

A mixed route of urban, rural and highway conditions was driven during the PEMS test. The scope in this case was to obtain a mix of operating conditions similar to those of the chassis dyno tests. It is acknowledged that the engine was optimized for urban use thus at low vehicle speeds and medium engine loads. The main characteristics of all driving cycles are summarized in Table 2.

Table 2. Main characteristics of PEMS driving cycle

	WHVC			ETC			PEMS		
	Urban	Rural	Motorway	Urban	Rural	Motorway	Urban	Rural	Motorway
Average Speed [km/h]	20	32	70	23	65	86	25-28	44-47	70-76
Distance [km]	3.9-4.2	3.8-3.9	11.7-12.0	3.4-3.8	9.1-11.0	14.7-14.8	3.6-8.3	38.2-48.8	53.6-66.5
Duration [s]	744	440	615	586	586	628	483-1391	2176-3577	2526-3757
Energy Work [kWh]	3.8-3.9	2.8-3.1	8.7-8.8	2.8-3.0	6.6-7.8	10.5-10.7	2.7-7.0	32.3-45.2	49.6-58.8

As it can be seen from Table 2, speed profile over PEMS is quite different from those of bench cycles particularly at its urban part, which involves higher speeds (Figure 8). Average speeds over the three parts over PEMS were 26-28 km/h, 44-47 km/h and 70-76 km/h, respectively. It should be pointed out that the speeds of the rural and highway part of ETC, as well as of the highway part of WHVC, exceed those experienced during the operation of a typical garbage collection truck. However, the selection of these cycles was based on the aim to follow the engine operation over certification-like conditions in addition to real world operation which was fully covered by on-road tests.

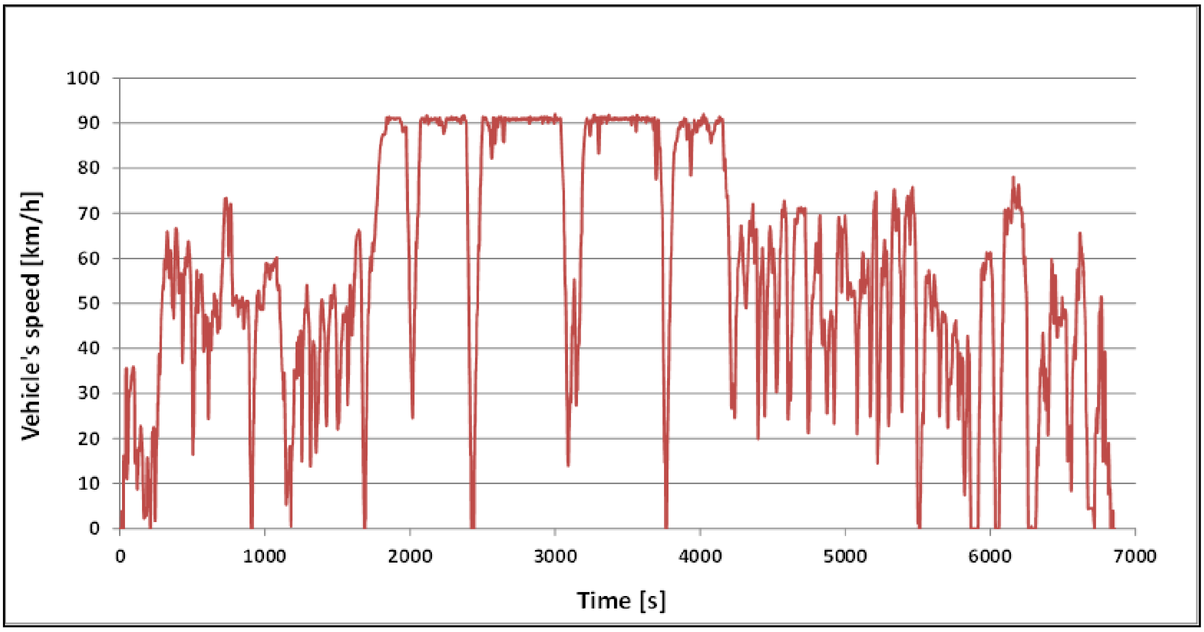


Figure 8. Speed vs time profile of on-road tests

Two sampling campaigns were performed. The first was conducted in January 2014 and involved the testing of the base engine both in VELA 7 and on-road with the PEMS system. At least, five tests over each cycle (ETC and WHVC) were performed and average emissions of all pollutants were determined. All measurements were conducted with a warmed up engine (hot-start), thus after conditioning of the engine over a constant speed for at least 10 min. Three measurements with PEMS were also conducted and average emissions of each pollutant were calculated. The second campaign was conducted in October 2014 and was an exact repetition of the first with the reference engine being replaced by the prototype.

2.3. EMISSIONS TESTING AND ANALYSIS

Chassis dyno measurements were performed at the Vehicle Emissions Laboratory (VELA) of the EC's Joint Research Centre (JRC). Figure 9 presents an overview of the VELA 7 facility built for HDV emissions, fuel consumption and performance testing [1].

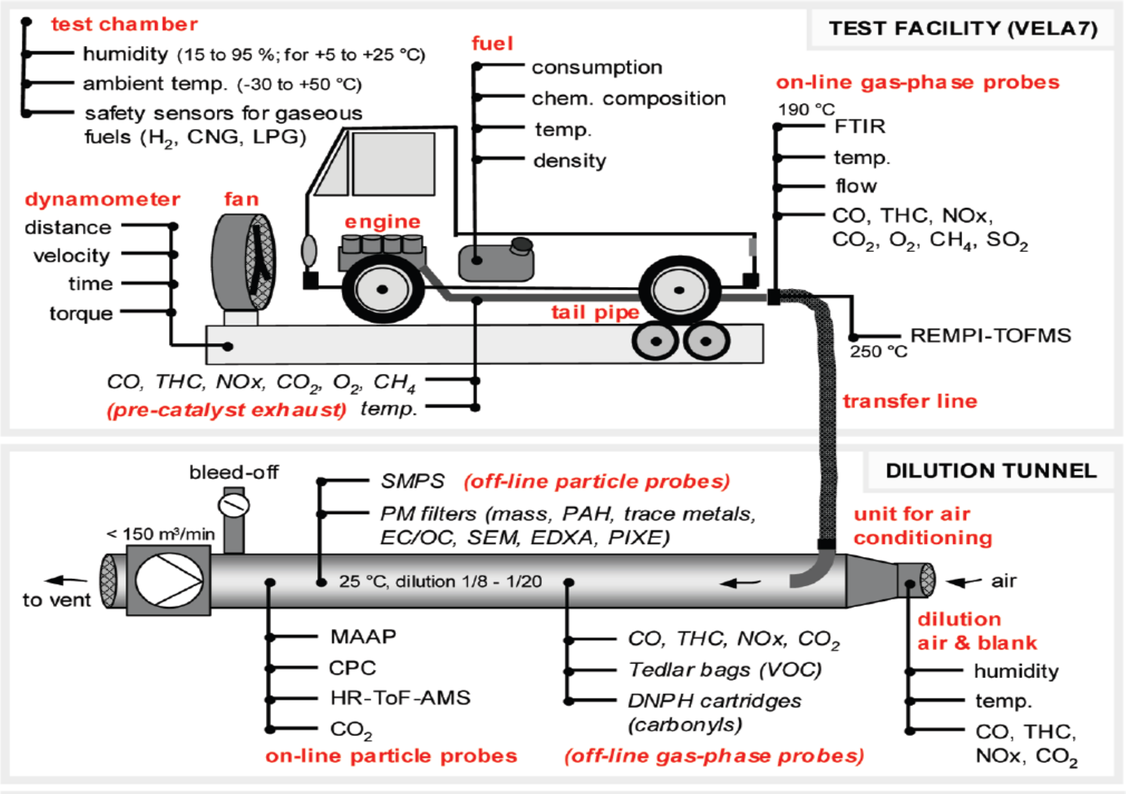


Figure 9. Overview of the VELA 7 test facility

The chassis dynamometer (Zoellner GmbH, Germany) has been designed to host heavy-duty vehicles (trucks and buses) of up to 30 tons in weight, 12 m in length, and 5 m in height. Maximal test speed is set at 150 km/h. The test cell can be conditioned between -30 and +50 °C with relative humidity of 15-95% providing the ability to test vehicles under extreme conditions. The constant-volume sampler (CVS) for full exhaust dilution (AVL, Graz, Austria) is equipped with 4 Venturis of 10, 20, 40, and 80 m^3/min in order to achieve a maximum aggregated air flow of 150 m^3/min. Dilution air is taken from the test cell, conditioned to 22°C, and filtered through high-efficiency particulate air (HEPA) and activated charcoal filters. The climatic test cell of VELA 7 has an air circulation system that provides enough number of cell air changes (≥15) in order to allow the testing of vehicles fueled with different types of fuels.

An AVL i60 AMA 4000 system was used for the analysis of emissions. A Heated Flame Ionization Detector (HFID) is employed for measuring exhaust gas concentrations of THC and CH_4. A Heated Non-Dispersive Infrared sensor (NDIR) is used for CO_2 and CO emissions. A Heated ChemiLuminescence Analyzer (CLD) measures exhaust NO_X. The measurement equipment is described in detail elsewhere [1, 16]. Pollutants were measured downstream of the exhaust aftertreatment system of the truck. The calculation of the engine work output over each sub-cycle was based on the instantaneous engine torque and rpm values which were recorded via the vehicle's OBD system. A cross validation with the instantaneous work values retrieved from the chassis dyno system was also performed and confirmed the accuracy of the calculation.

On-road testing reflects the normal use of a vehicle, such as influence of ambient temperature, topography, vehicle/engine load and driving patterns [12]. The PEMS system used in all on-road tests was the Semtech-DS manufactured by Sensors, Inc. and it consists of tailpipe attachment, heated exhaust lines, an exhaust flow meter, exhaust gas analyzers, data logger to vehicle network, a global positioning system (GPS), and a weather station for ambient temperature and humidity. All data was recorded at a frequency of 1 Hz and the whole system ads further ~100 kg of instrumentation to the vehicle besides the weight of the driver (~80 kg). The Semtech DS measures exhaust gas concentrations of unburned hydrocarbons (THC) by HFID, carbon monoxide (CO) and carbon dioxide (CO_2) by a NDIR, and nitrogen monoxide (NO) and nitrogen dioxide (NO_2) by a non-dispersive ultra-violet sensor (NDUV). Table 3 provides the main characteristics of the PEMS system [Fontaras et al. 2013]. The oxides of nitrogen (NO_X) are calculated by the sum of the concentrations of NO and NO_2. The measurement principles and accuracy from the Semtech DS are in-line to those described by current legislation for this type of testing [17]. As a standard procedure, test runs preparation included routine calibration of pollutant analyzers (zero and span of gases).

Table 3. Main characteristics of the PEMS system

	Method	**Range**	**Accuracy**
CO_2	NDIR	0-20%	±0.1% or ±3% of reading
CO	NDIR	0-8%	50 ppm/±3% of reading
THC	HFID	0-100 ppm	5 ppm/±2% of reading
NO	NDUV	0-2500 ppm	15 ppm/±3% of reading
NO_2	NDUV	0-500 ppm	10 ppm/±3% of reading

3. RESULTS AND DISCUSSION

3.1. CARBON DIOXIDE EMISSIONS

CO_2 is the primary GHG gas and its emissions along with these of CH_4 are of high concern both for economy and environmental reasons. Despite that CO_2 emissions are not regulated, in 2014 the EC adopted a communication entitled **"Strategy for reducing HDV fuel consumption and CO_2 emissions"** which emphasizes the need for reducing them. Power specific CO_2 emissions of the prototype engine were approximately 660 g/kWh and 715 g/kWh for the WHVC and ETC cycles, respectively, and were lower compared to those reported in the literature for EURO V and EEV standard CNG HDVs [6, 12-13]. On-road CO_2 of the prototype engine accounted for 688 g/kWh, and was at the same level with to those given in the literature for EEV standard CNG buses [6, 12]. According to available literature data CO_2 emissions of the prototype engine are significantly lower compared to those of in-use HD diesel engines [3, 13-14]. These comparisons are very promising regarding the use of the prototype engine as alternative to diesel engines particularly for urban applications. Figure 10 provides a summary of specific CO_2 emissions over the different part of the cycles (Urban, Rural and Motorway) both for chassis dyno and on-road tests.

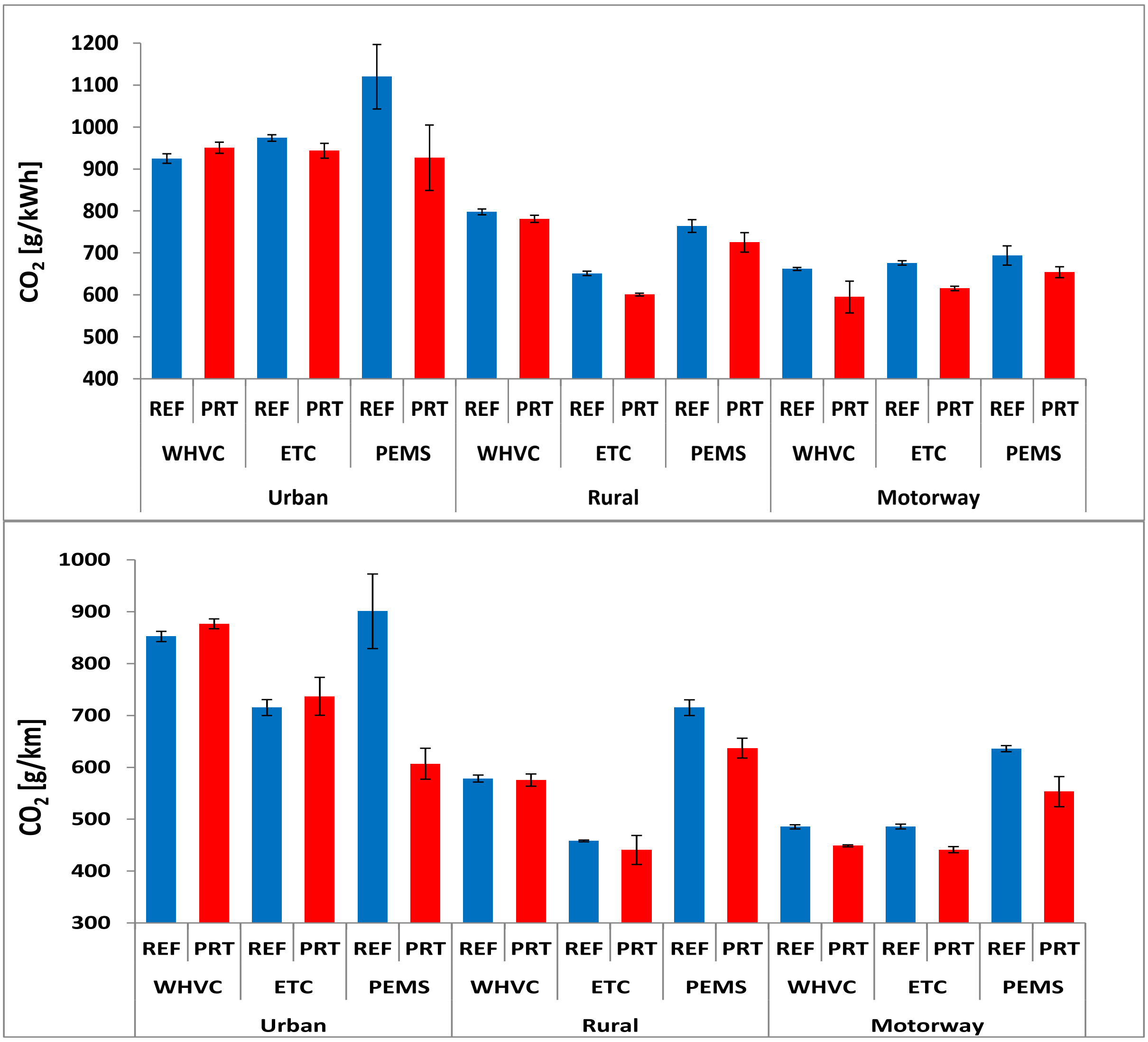


Figure 10. (a) Specific CO_2 emissions over the different parts of the cycles performed on the chassis dynamometer and on-road. (d) Distance specific CO_2 emissions over the different parts of the cycles performed on the chassis dynamometer and on-road. Error bars correspond to ±standard deviation.

Like in case of energy specific emissions there is a general reduction of the distance specific CO_2 emissions with the introduction of the prototype compared to the base engine (Figure 10b). Emissions with the prototype engine vary from 478 to 584 g/km, and are significantly lower than those reported in the literature [3, 12-14].

CO_2 emissions with the prototype engine are 6.5% and 5.0% lower compared to those of the reference engine over ETC and WHVC, respectively. On road tests exhibited similar results with the reduction in this case reaching 8.4%. CO_2 reduction with the prototype engine is observed over all three phases and over all tested speeds (Figure 11). However, the reductions are more pronounced over rural and motorway phases, which are the best conditions to obtain good performances by the VVA device. This is due to higher pumping friction saving with the prototype engine at medium and low loads.

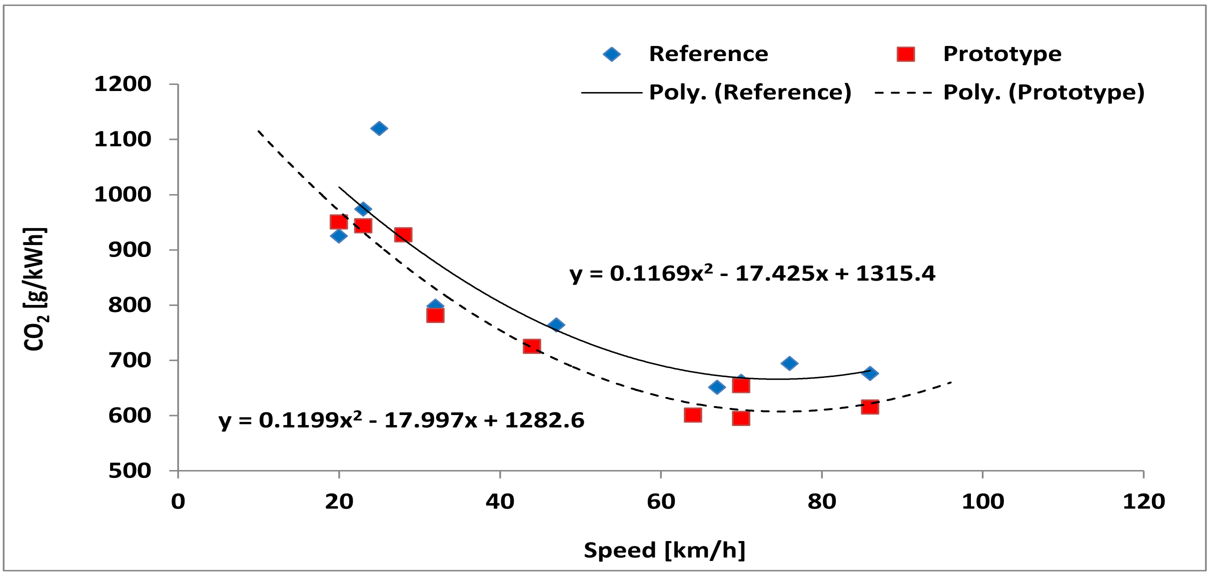


Figure 11. Comparison of CO_2 emissions from the reference and the prototype engine over different speeds

3.2. NITROGEN OXIDE EMISSIONS

Total NO_x emissions of the prototype engine were below the EURO V and EEV emission standard under all test conditions. Some exceedances were observed with the reference engine over low speed conditions (Figure 12a). NOx emissions of the prototype engine over the chassis dynamometer tests varied from 0.67 g/kWh to 0.97 g/kWh, while on-road emissions were 0.63 g/kWh. Figure 12a shows that NO_x emissions were higher than the EURO VI limit mainly due to higher emissions over low and medium speed phases. This observation has also been reported elsewhere [14]. However, NO_x emissions of the prototype engine are still significantly lower compared to those reported in the literature for diesel engines [6, 12-15], comprising thus a very good alternative for urban applications.

Distance specific NO_x emission levels with the prototype engine vary from 0.48 to 0.76 g/km, and are significantly lower compared to those reported in the literature for CNG trucks and buses [13-14]. Figure 12b shows that, like in case of energy specific NO_x emissions, higher emissions are recorded over low and medium speed phases. On the other hand, NO_x emissions of the motorway phase are lower due to more complete air-fuel ratio control at this part of the engine map and consequently to optimum conditions for the stoichiometric combustion.

NO_x emissions with the prototype engine are reduced by 37% and 61% compared to those of the reference engine over ETC and WHVC, respectively. On road tests exhibited similar results with the reduction in this case reaching 50%. NO_x reduction with the prototype engine is more pronounced over low and medium speed conditions (Figure 13). The reduction achieved with the prototype engine can be attributed to the effective counterbalance of the higher spark advance in case of the VVA system by the over expansion that results in decreased mean temperatures of the combustion phase.

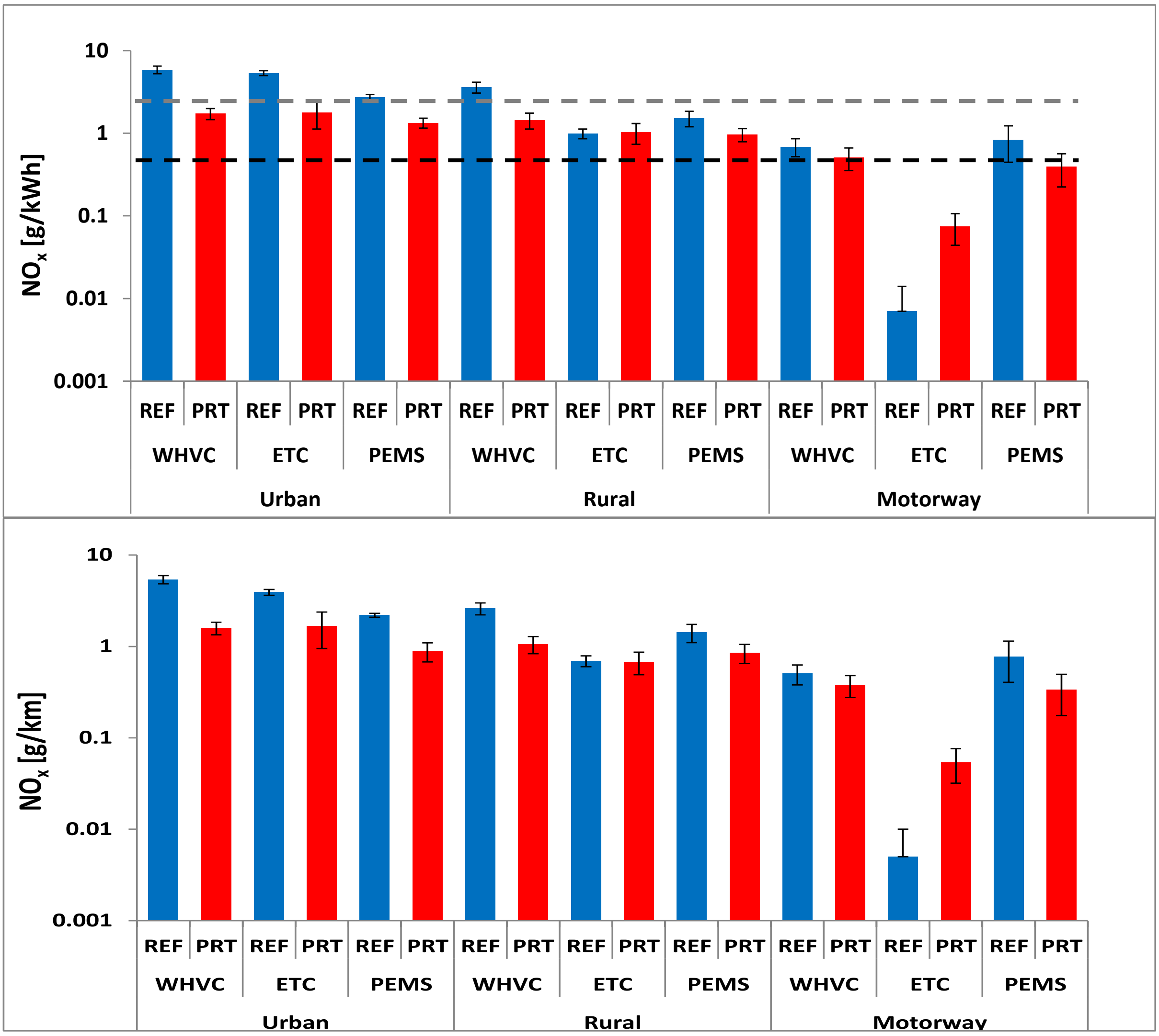


Figure 12. (a) Specific NO$_x$ emissions over the different parts of the cycles performed on the chassis dynamometer and on-road. (d) Distance specific NO$_x$ emissions over the different parts of the cycles performed on the chassis dynamometer and on-road. Error bars correspond to ±standard deviation. Dashed lines represent the limit values of the Euro V (gray) and Euro VI (black) standard.

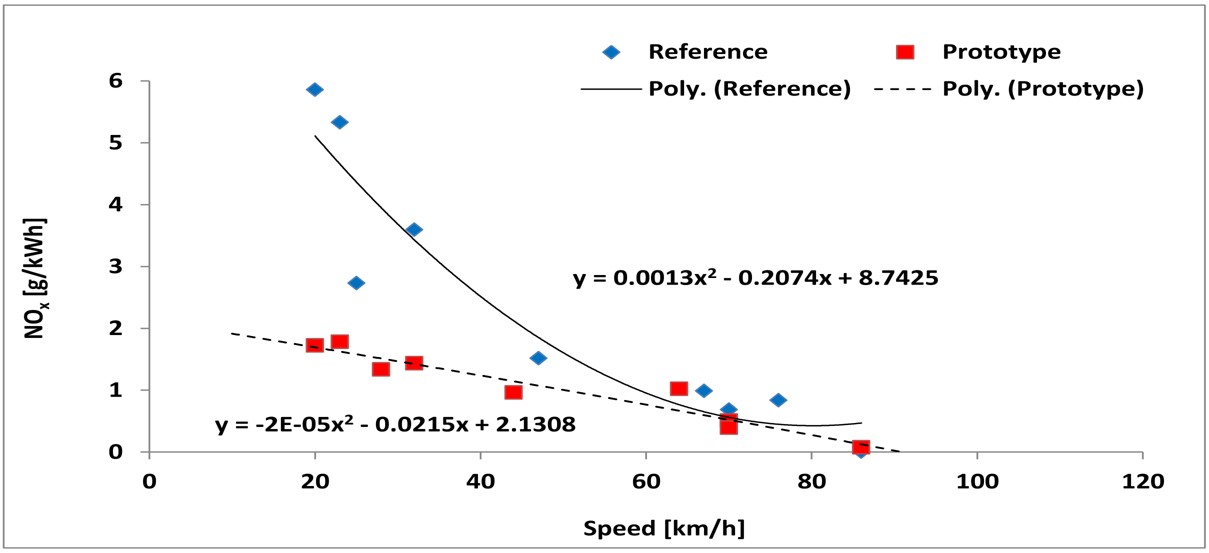


Figure 13. Comparison of NO$_x$ emissions from the reference and the prototype engine over different speeds

3.3. CARBON MONOXIDE EMISSIONS

Total CO emissions of both engines were below the common EURO V and EURO VI emission standard (4.0 g/kWh) under all testing conditions. Figure 14a shows that CO emissions of the prototype engine were below the regulated limits, regardless the speed and operating mode. Lower CO was emitted at low and medium operating modes of the lower speed parts, where mostly garbage collection trucks operate, and is a result of leaner combustion under these conditions due to heavier acceleration phases. This can result in a not perfect air-fuel ratio control, and thus more oxygen available in the combustion chamber to oxidize CO. Similar observations have also been made elsewhere [14]. CO emissions of CNG stoichiometric engines, like the one used for the purposes of the current study, are reported in the literature to be slightly higher compared to those of diesel engines equipped with traps [12-15]. Also in this case, CO emissions of the prototype engine are comparable, and sometimes lower, to those reported in the literature for modern diesel engines.

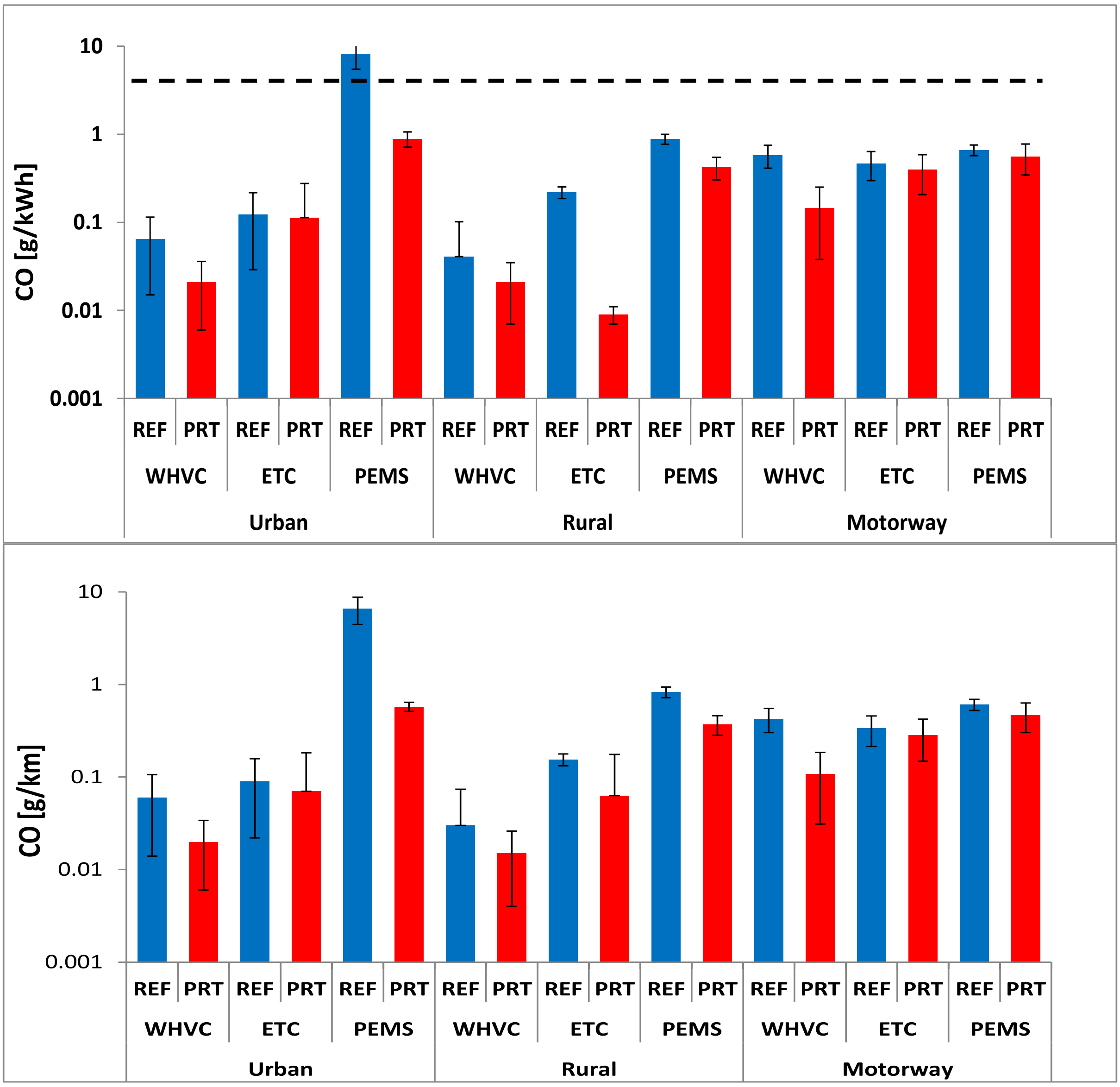


Figure 14. (a) Specific CO emissions over the different parts of the cycles performed on the chassis dynamometer and on-road. (d) Distance specific CO emissions over the different parts of the cycles performed on the chassis dynamometer and on-road. Error bars correspond to ±standard deviation. Dashed line represents the limit value of the Euro V and Euro VI standard.

CO distance specific emissions with the prototype vary from 0.07 g/km (WHVC) to 0.44 g/km (PEMS), and are significantly lower compared to those reported by Fontaras et al. [13] for two EURO V waste collection CNG trucks tested on-road (1.0-1.7 g/km). Much higher distance specific CO emissions have been reported for CNG buses tested under different conditions [3,6, 12, 15]. Even if these results are not comparable to those of the current study due to different driving cycles and testing conditions, they are however indicative of the improvement achieved in terms of CO emissions with the introduction of the VVA system.

A reduction of CO emissions with the prototype engine of 27% and 74% over ETC and WHVC, respectively was recorded. On road tests showed 58% less CO emissions with the prototype compared to the reference engine. As seen from Figure 15, CO reductions are more pronounced at low and medium speed conditions, while at higher speeds the emissions of the two engines are similar. As explained previously, at higher speeds the combustion is almost stoichiometric for both engines therefore no advance over CO emissions is expected. Also due to the catalyst very low emissions are expected at hot operation. The reduction in CO emissions with the prototype engine is due to a longer ending phase of combustion with the VVA system which eliminates freezing phenomena and contributes to the complete oxidation of carbon molecules.

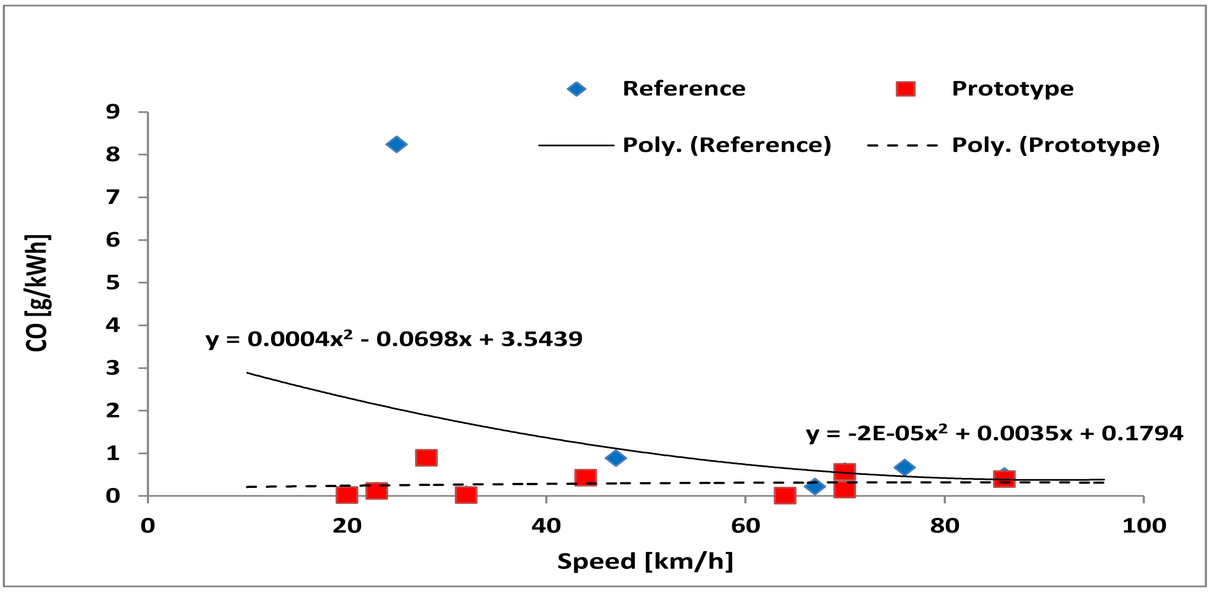


Figure 15. Comparison of CO emissions from the reference and the prototype engine over different speeds

3.4. TOTAL HYDROCARBON EMISSIONS

THC emissions of the prototype engine ranged from 0.39 g/kWh (WHVC) to 0.56 g/kWh (ETC), which is significantly higher to those found for the reference engine. THC emissions of the prototype are generally considered high with respect to the EURO VI limits for CH_4 and NMHC. As seen from Figure 16a the highest THC emissions of the prototype engine are observed under low speed conditions (0.53-2.08 g/kWh), where mostly refuse hauler vehicles operate. Under these conditions the catalyst temperature of the prototype engine is lower than that of the reference engine, thus affecting its efficiency negatively. Similar results have been reported elsewhere [14]. In the current study, THC emissions of the prototype engine are comparable to those of HD diesel engines used in trucks [13-14], but still higher from those of HD diesel city buses [6, 12].

THC distance specific emissions follow the same trend as energy specific emissions. THC emissions with the prototype engine vary from 0.30 g/km (PEMS) to 0.41 g/km (ETC) and are lower compared to those reported in the literature for CNG HDV [13-14]. Similar THC emissions have been reported for CNG buses tested over different conditions [3, 6, 12, 15]. Despite the fact that THC emission levels of the prototype engine are low compared to those found in the literature, some improvement maybe required in order to optimize this engine with regard to THC emissions in order to make it ideal for urban applications such as garbage collection purposes.

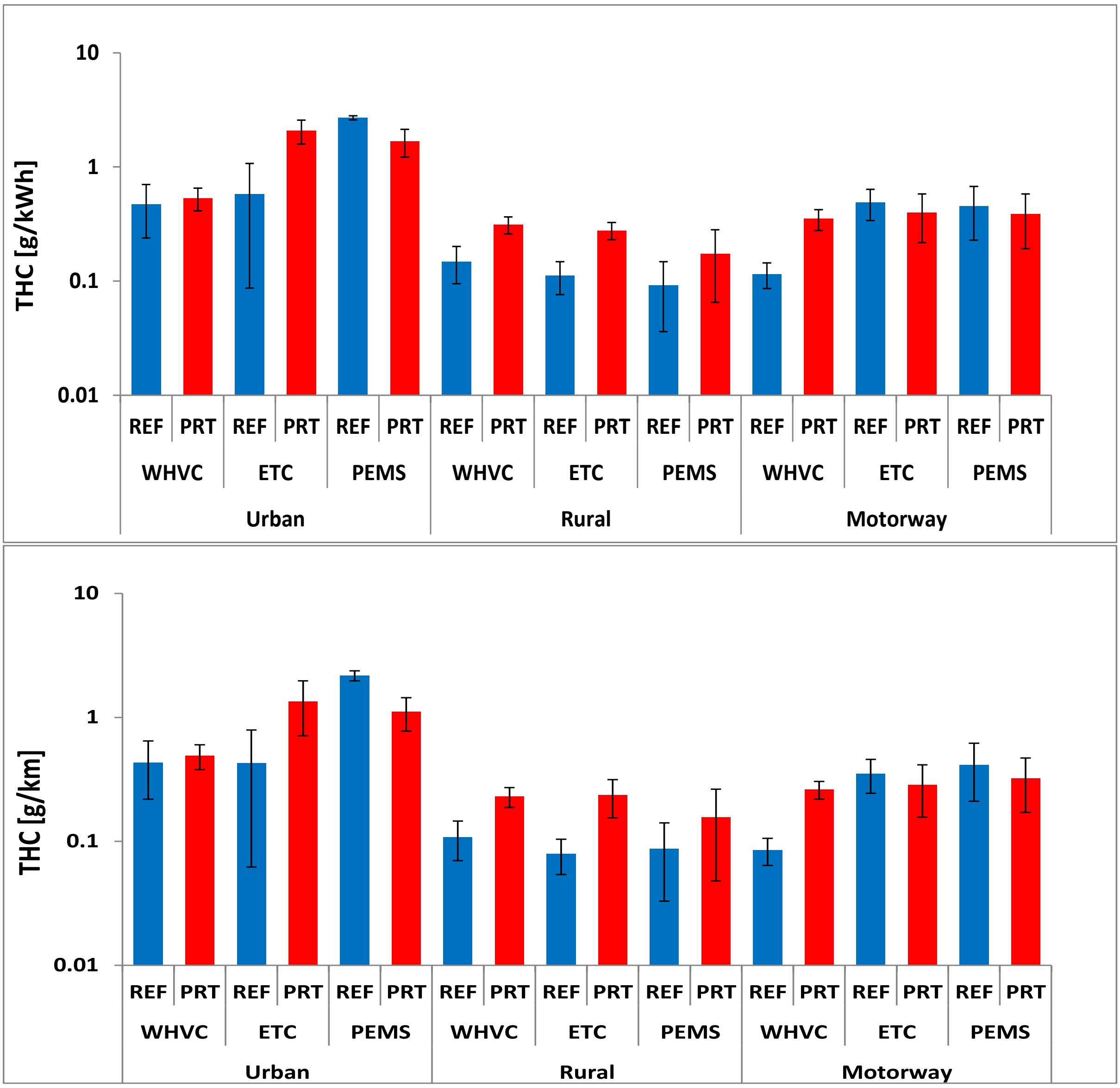


Figure 16. (a) Specific CO emissions over the different parts of the cycles performed on the chassis dynamometer and on-road. (d) Distance specific CO emissions over the different parts of the cycles performed on the chassis dynamometer and on-road. Error bars correspond to ±standard deviation.

The introduction of the prototype engine results in increased THC emissions by 54% and 85% over ETC and WHVC, respectively, suggesting that more fuel escapes unburned with the prototype engine (since THC comprise mainly from CH_4). This phenomenon is more pronounced over low and medium power modes of the urban and rural parts, while at the motorway part THC emissions are less affected and sometimes even decrease with the prototype engine (Figure 17). The catalyst temperature with the prototype engine is lower at low loads, thus resulting in higher THC emissions, while at higher speeds this affect is eliminated. On the other hand, on-road THC emissions reduced by 17% with the prototype engine. Higher average speeds at the urban part of PEMS, as well as the longer motorway part of on-road tests compared to ETC and WHVC could possibly explain the different behavior of THC emissions among dynamometer and on-road tests.

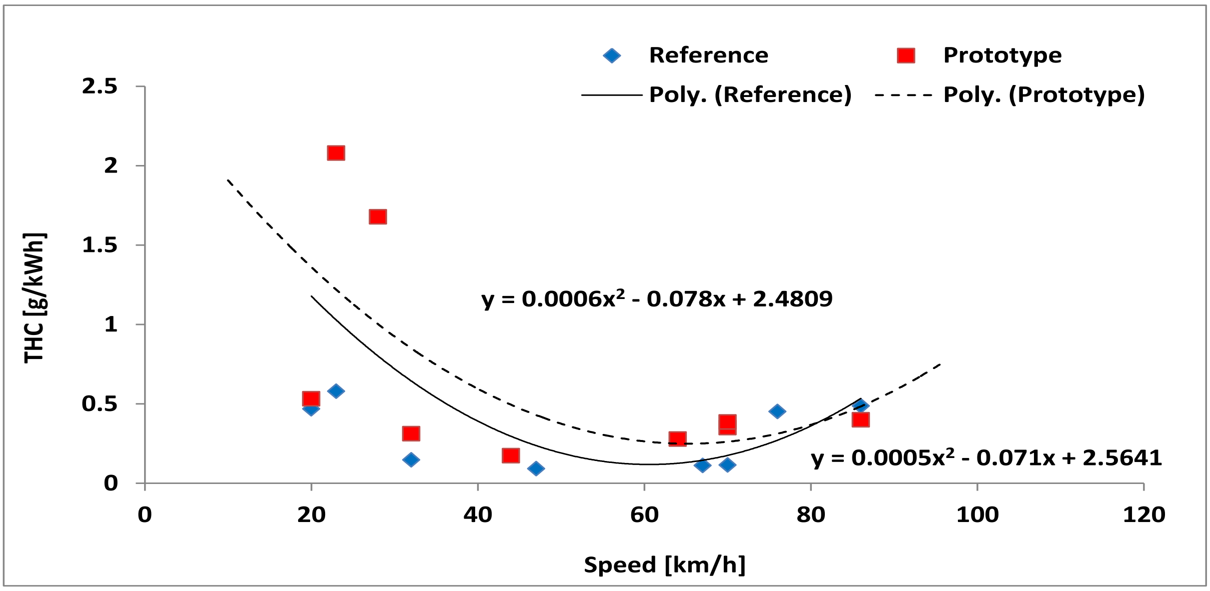


Figure 17. Comparison of THC emissions from the reference and the prototype engine over different speeds

3.5. METHANE EMISSIONS

Methane is the major constituent of THC emissions and as a GHG its emissions are of high concern. CH_4 emissions of both engines were below the EURO V emission standard (1.1 g/kWh) under all test conditions. CH_4 emissions of the prototype engine ranged from 0.30 g/kWh (WHVC) to 0.53 g/kWh (ETC). The latest are considered to be high with respect to the EURO VI standard limit and would require adequate catalyst conversion efficiency in order to be reduced. Similar emissions have been reported in the literature [6, 12]. The highest methane emissions of both engines were observed at the urban phase of the tested cycles, following the trend described for THC emissions. When comparing methane emissions from CNG and diesel engines, it is clear that the CNG engines emit much higher due to the fact that the fuel practically comprise of compressed CH_4. This is confirmed with the CH_4 emissions of the prototype engine which are higher than those reported for HD diesel engines elsewhere [12-14].

The introduction of the prototype engine had also a negative effect on the distance specific methane emissions over the chassis dynamometer transient cycles (Figure 18b). Distance specific CH_4 emissions with the prototype engine varied from 0.23 g/km (WHVC) to 0.27 g/km (ETC), and were lower compared to those reported for CNG trucks in the literature [14]. Again, some improvement would be necessary in order to avoid exceedances of CH_4 emissions and optimize the prototype engine for urban applications such as garbage collection purposes.

The prototype engine emits 56% (ETC) and 52% (WHTC) more CH_4 than the reference engine. This confirms the assumption that more CH_4 escapes unburned in the case of the prototype engine. Figure 19 shows that the increase in CH_4 emissions over chassis dyno tests is more pronounced over urban and rural parts of the cycles, while at the motorway part there is practically no difference. As explained previously, the catalyst temperature reached with the prototype engine is the driving parameter for higher THC and thus methane emissions. Unfortunately, there were no CH_4 emissions measurements conducted on-road, therefore no safe conclusions regarding the trends recorded could be drawn.

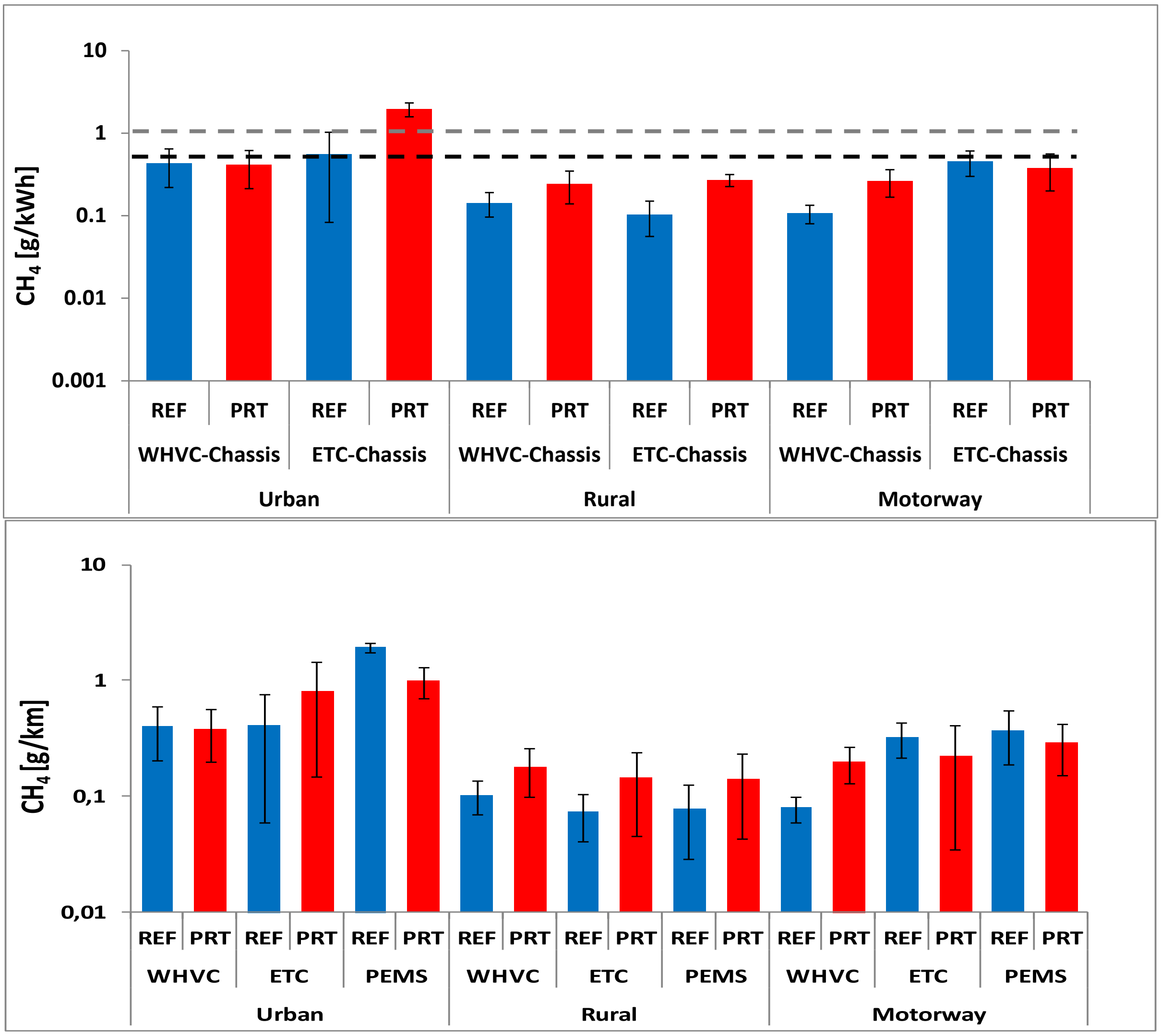


Figure 18. (a) Specific CH_4 emissions over the different parts of the cycles performed on the chassis dynamometer and on-road. (d) Distance specific CH_4 emissions over the different parts of the cycles performed on the chassis dynamometer and on-road. Error bars correspond to ±standard deviation. Dashed lines represent the limit values of the Euro V (gray) and Euro VI (black) standard.

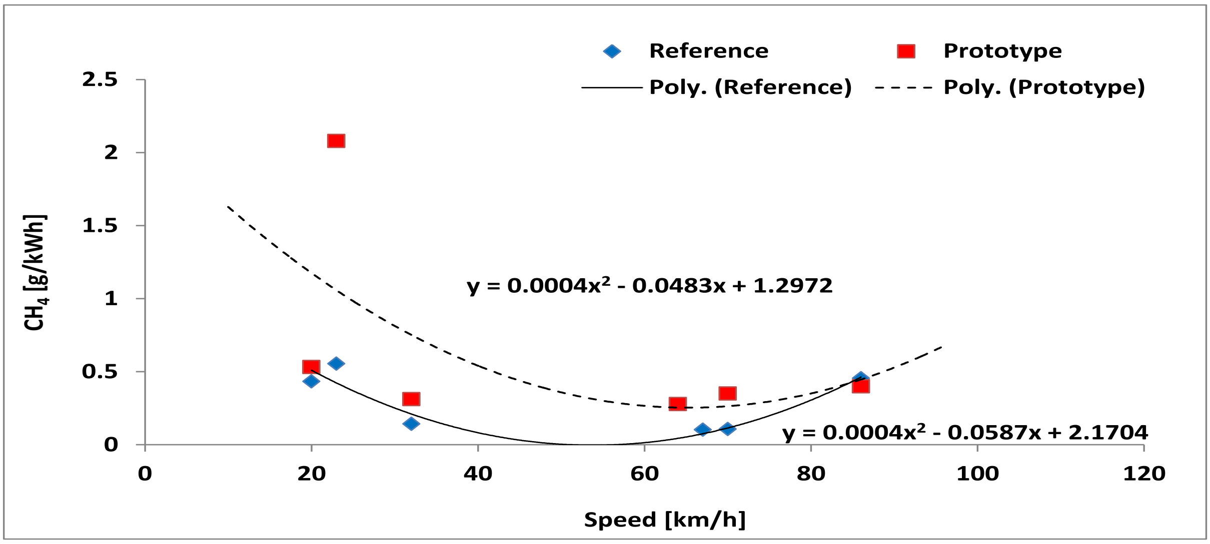
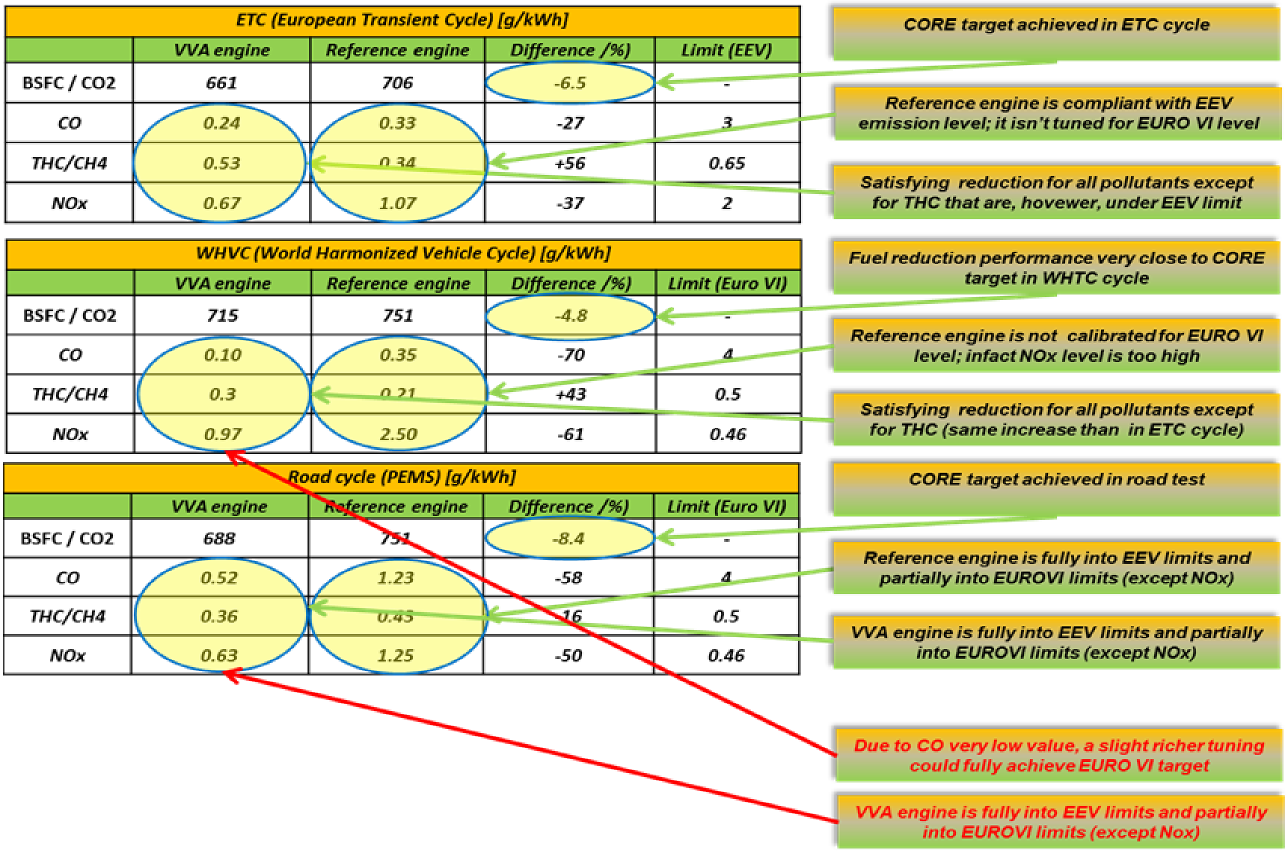


Figure 19. Comparison of CH_4 emissions from the reference and the prototype engine over different speeds

4. CONCLUSIONS

The prototype engine developed in the framework the 7th Framework Programme research project **“CO_2 Reduction for long distance transport”** was benchmarked against its parent CNG engine in terms of real-operation emissions, and achieved a significant reduction in CO_2 emissions and fuel consumption. Additionally, significant NO_x and CO reductions were achieved, while all results were confirmed under real-life operating conditions. On the other hand, significant THC and CH_4 emissions increases were observed with the introduction of the prototype engine, without however this trend confirmed under real-life operating conditions. Figure 20 provides an overview of the emissions of both engines under all testing conditions, along with the difference achieved with the introduction of the prototype engine. Accompanying comments provide an overview with regard to the target of the overall project as it is presented in Figure 21. Figures 20 and 21 were adopted from the 17.3 deliverable of the CO_2Re project.



ETC (European Transient Cycle) [g/kWh]				
	VVA engine	Reference engine	Difference /%)	Limit (EEV)
BSFC / CO2	661	706	-6.5	-
CO	0.24	0.33	-27	3
THC/CH4	0.53	0.34	+56	0.65
NOx	0.67	1.07	-37	2

WHVC (World Harmonized Vehicle Cycle) [g/kWh]				
	VVA engine	Reference engine	Difference /%)	Limit (Euro VI)
BSFC / CO2	715	751	-4.8	-
CO	0.10	0.35	-70	4
THC/CH4	0.3	0.21	+43	0.5
NOx	0.97	2.50	-61	0.46

Road cycle (PEMS) [g/kWh]				
	VVA engine	Reference engine	Difference /%)	Limit (Euro VI)
BSFC / CO2	688	751	-8.4	-
CO	0.52	1.23	-58	4
THC/CH4	0.36	0.43	-16	0.5
NOx	0.63	1.25	-50	0.46

CORE target achieved in ETC cycle

Reference engine is compliant with EEV emission level; it isn't tuned for EURO VI level

Satisfying reduction for all pollutants except for THC that are, hovewer, under EEV limit

Fuel reduction performance very close to CORE target in WHTC cycle

Reference engine is not calibrated for EURO VI level; infact NOx level is too high

Satisfying reduction for all pollutants except for THC (same increase than in ETC cycle)

CORE target achieved in road test

Reference engine is fully into EEV limits and partially into EUROVI limits (except NOx)

VVA engine is fully into EEV limits and partially into EUROVI limits (except NOx)

Due to CO very low value, a slight richer tuning could fully achieve EURO VI target

VVA engine is fully into EEV limits and partially into EUROVI limits (except Nox)

Figure 20. Pollutant emissions of both engines and difference achieved with the introduction of the prototype engine

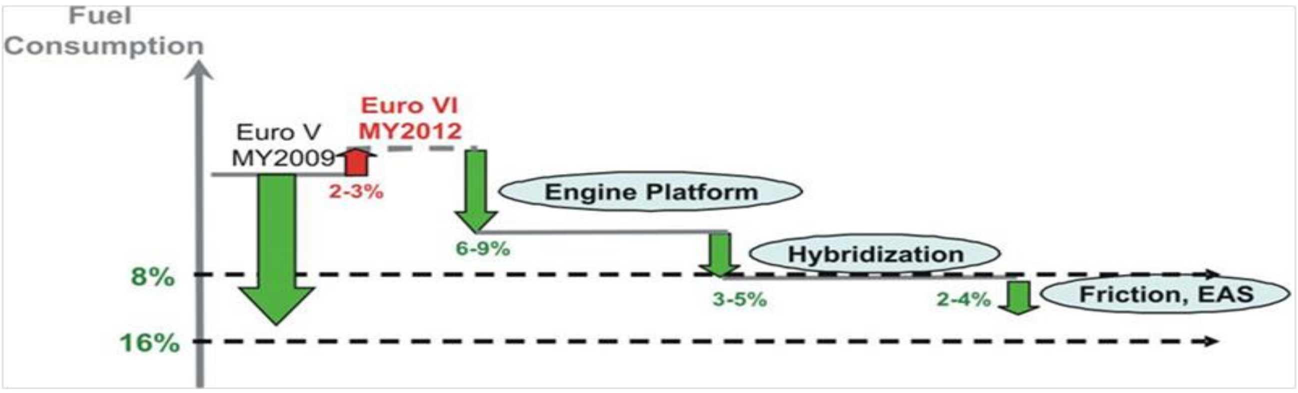


Figure 21. CO_2RE project target deployment

In the Figure 21 a graph extracted by the CO_2RE description of work document is presented. The desiderated target for overall decrease of 16% fuel consumption is demonstrated. With regard to this target the CNG engine platform had to demonstrate the possibility to obtain a reduction coming from 6% to 9% (as written in Form B.1 and shown in the graph). Testing results revealed a reduction ranging from 5% to 8.4% with an average value of 6.5%, fully in target with the CO_2RE project objective.

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