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Evaluation of a Euro 4 vehicle with various blends of CNG/H_2 fuel

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1 INTRODUCTION

The use of alternative fuels has been stimulated by the European Commission in EN 2009/30/EC [1], which requires fuel supplier to achieve at least 6% Greenhouse Gas (GHG) saving from fuels supplied on 2020 with intermediate targets: 2% by 31 December 2014 and 4% by 31 December 2017. The commission also requires Member States to meet 10% renewable energy share in the transport sector by 2020 (EN 2009/28/EC – Renewable Energy Directive) [2].

Regulation (EC) No 79/2009 of the European Parliament and of the Council [3] on type-approval of hydrogen-powered motor vehicles, and amending Directive 2007/46/EC [4] was published in the Official Journal on 4 February 2009. The main objective of the Regulation is to ensure the proper functioning of the internal market for hydrogen-powered motor vehicles by specifying harmonised safety requirements. The Regulation will facilitate the approval and placing on the market of these environmentally friendly vehicles throughout the European Union (EU).

The Regulation uses the so-called 'split level' approach that has been applied in the case of other automotive legislative acts, for instance with the Euro 5 and 6 stage of light-duty vehicle emission standards.

However, during the review of the existing type-approval directives and regulations on the environmental performance of vehicles there were found some open issues regarding vehicles using mix of Hydrogen (H_2) and Compressed Natural Gas (CNG), in particular there were no methods for type approval of these types of vehicles using a variable mixture of H_2-CNG.

The Joint Research Centre (JRC) has been working in support to Directorate General Enterprise and Industry (DG-ENTR), which is in charge of the related file, for the development of the above mentioned Regulation for several years. The JRC has provided support to DG ENTR by running an experimental programme on specific issues related to H_2 and H_2-CNG mixture emissions legislation. In particular the JRC has carried out experimental work to evaluate the emission levels of H_2-CNG fuelled vehicles.

This report presents the principal results of the experimental evaluation programme for the emission levels of this class of vehicles.

2 EXPERIMENTAL METHODS

2.1 TEST VEHICLE

The vehicle tested in this study was a Light duty vehicle (category M1), equipped with a multi-fuel engine (petrol, methane and mixture H_2-CNG). It was provided by Research Centre Fiat [5]. The specific model was not available in the market, but it was based on the respective bi-fuel (petrol and CNG) model configuration. The latter was a Euro 4 compliant, Port Fuel Injection (PFI) vehicle equipped with a Three Way Catalyst (TWC). Table 1 provides the main characteristics of the tested vehicle.

Table 1: Vehicle data and specifications.

Vehicle model	Fiat Panda Natural Power	
Fuel	Petrol	Methane (CNG)
No. of Cylinders	4	
Aspiration	Atmospheric	
Fuel Delivery	Multi point port Injection	
Capacity [cm^3]	1248	
Kerb Weight [kg]	1050	
Power [kW @ rpm]	44 @ 5000	38 @ 5000
Torque [Nm @ rpm]	102 @ 2500	88 @ 3000
Maximum Speed [km/h]	148	140
Transmission	Manual – 5 gears	

Table 2 provides the type approval Carbon Dioxide (CO_2) emissions and fuel consumption over the New European Driving Cycle (NEDC), the Urban Driving Cycle (UDC) and the Extra Unban Driving Cycle (EUDC). The gaseous (Carbon Monoxide (CO), Hydrocarbons (HC), Nitrogen Oxides (NO_x)) over the NEDC for Type 1 test are also shown. The last column of Table 2 provides the Euro 4 limits for each pollutant. The presented type approval data refer to the bi-fuel petrol – CNG model in which was based on the tested vehicle.

Table 2: Type approval gaseous emission performance and Fuel Consumption of the tested vehicle.

Driving Cycle	**ECE**		**EUDC**		**NEDC**		**Type I Euro 4 limit**
	Petrol	CNG	Petrol	CNG	Petrol	CNG	
CO_2 [g/km]	185	145	123	96	146	114	
Fuel Consumption [l/100km]	7.9	5.3	5.2	3.5	6.2	4.2	
CO [g/km]					0.395		1
HC [g/km]					0.028		0.1
NO_x [g/km]					0.031		0.080

2.2 TEST FUELS

The test vehicle was initially fuelled with a commercial petrol meeting the fuel quality requirements for petrol vehicles, without ethanol content (E0). Afterwards it was fuelled by certified blends of hydrogen and methane (H_2-CNG) with H_2 content ranging from 0 to 30 (%v/v); i.e. from pure CNG to 30%H_2-70%CNG for both methane quality (G20 and G25). The different certified characteristics of these fuels can be found in the Annex I and Annex II. Table 3 shows the fuel matrix used in this work, as well as the nominal and the actual composition of the different compounds.

Table 3: Fuel matrix (nominal and actual composition).

Test Fuel	**Fuel Type**	**H_2 [%] Nominal**	**H_2 [%] Analysis**	**N_2 [%] Analysis**	**CH_4 [%] Calculated**
F1	Commercial petrol (E0)	-	-	-	-
F2	70% CNG G20 + 30% H_2 (CRF)	30	-	-	70 (nominal)
F3	100% CNG G20 (JRC)	0	-	-	100 (nominal)
F4	70% CNG G20 + 30% H_2 (JRC)	30	29.60	-	70.40
F5	75% CNG G20 + 25% H_2 (JRC)	25	25.10	-	74.90
F6	80% CNG G20 + 20% H_2 (JRC)	20	19.90	-	80.10
F7	85% CNG G20 + 15% H_2 (JRC)	15	15.03	-	84.97
F8	90% CNG G20 + 10% H_2 (JRC)	10	10.03	-	89.97

F9	95% CNG G20 + 5% H_2 (JRC)	5	5	-	95
F10	100% CNG G25 (JRC)	0	-	14 (nominal)	86 (nominal)
F11	70% CNG G25 + 30% H_2 (JRC)	30	30.17	9.64	60.19
F12	75% CNG G25 + 25% H_2 (JRC)	25	24.25	10.37	65.38
F13	80% CNG G25 + 20% H_2 (JRC)	20	19.93	11.19	68.88
F14	85% CNG G25 + 15% H_2 (JRC)	15	14.70	11.78	73.52
F15	90% CNG G25 + 10% H_2 (JRC)	10	10.06	12.47	77.47
F16	95% CNG G25 + 5% H_2 (JRC)	5	5.04	13.15	81.81

2.3 TEST PROCEDURE

Emissions testing as part of the type approval procedure for light-duty vehicles is regulated within the European Union by the Co-decision regulation No. 715/2007 of 20 June 2007 [6] and the Commitology regulation No. 692/2008 of 18 July 2008 [7]. These regulations shall apply to vehicles of categories M_1, M_2, N_1 and N_2 as defined in Annex II to Directive 70/156/EEC [8] with reference mass not exceeding 2840 kg.

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

I. Total Hydro Carbons (THC)
II. Non-Methane Hydro Carbons (NMHC)
III. Nitrogen Oxides (NO_x)
IV. Carbon Monoxide (CO)
V. Particulate Matter (PM) in the case of PI vehicles with direct injection engines

The European emission legislation includes additional provisions, such as requirements for low temperature emission tests at -7°C for gasoline vehicles, which have to comply with limits of 15 g/km for CO and 1.8 g/km for HC, measured over the UDC [9, 10]. Carbon dioxide emissions are currently unrestricted at the level of individual vehicles. The European Commission, however, defines a target for the fleet-average CO_2 emissions of new passenger cars of 130 g/km for a reference car mass of 1372 kg [11].

However, the vehicle under test has been type approved as compliant with the type approval of light duty vehicle regulated within the European Union with Directive 70/220/EEC [12], as amended by Directive 98/69/EC [9] and 2003/76/EC [13]; i.e. Euro 4. The emission limits of the regulated pollutant according to this type approval (Euro 4) for vehicles equipped with PI engines have already presented in the last column of Table 2.

The compliance of light-duty vehicles with applicable emission limits is verified by emissions testing on the chassis dynamometer in the laboratory. The next section describes in detail the key characteristics of the procedure (driving cycle, measurement equipment).

2.4 INSTRUMENTATION DETAILS

The emission tests were carried out in a test cell equipped with a chassis dynamometer and a Constant Volume Sampling (CVS) system. The measurements were performed according to the current legislative procedures for type approval (UNECE Regulation 83 [14]). The bag gaseous emissions were available for the whole cycle as well as for the urban and extra-urban parts of the driving cycle (UDC and EUDC respectively). The vehicle was subjected to Type I test (verifying the average exhaust emissions after a cold start).

The measurements were conducted in the Vehicle Emission Laboratory (VELA) test cell of the JRC. The CVS was equipped with four critical orifices that allow the selection of the most appropriate flow rate from a minimum of 3.1 m^3/min to a maximum of 30.8 m^3/min. For this testing programme a CVS flow rate of 6 m^3/min was selected.

A Horiba MEXA-7400HTR-LE analyzer bench was employed for bag gaseous emission measurement (NO_x, total HC, Methane (CH_4), CO and CO_2). In addition, second by second data of emission concentrations in the raw exhaust were also recorded at the exit of the exhaust line (tailpipe). The real time traces of Oxygen (O_2), CO_2, CO and HC provided the means for the calculation of lambda.

The roller bench of the chassis dynamometer was a single roller type manufactured by MAHA GmbH with roller diameter: 48 in, maximum traction force: 3300 Nm, inertia range: 454-2720 kg, maximum speed: 200 km/h.

As far as the dynamometer's settings are concerned, the dynamometer loads prescribed by the legislation were used (Type I test, 22°C) since the actual road coast down data were not available for the tested vehicle.

Figure 1 presents a schematic diagram of the test vehicle setup. The test shell temperature and the relative humidity were kept constant during the tests and the soak period at 22°C and 50% respectively. Additional tests were run with E0 petrol fuel at 15°C and 25°C. For the tests conducted with gaseous fuels, the CNG/H_2 mixtures were delivered to the engine by gas bottles. The bottles had been previously fed with each CNG/H_2 blend and had sent for analysis in an external laboratory.

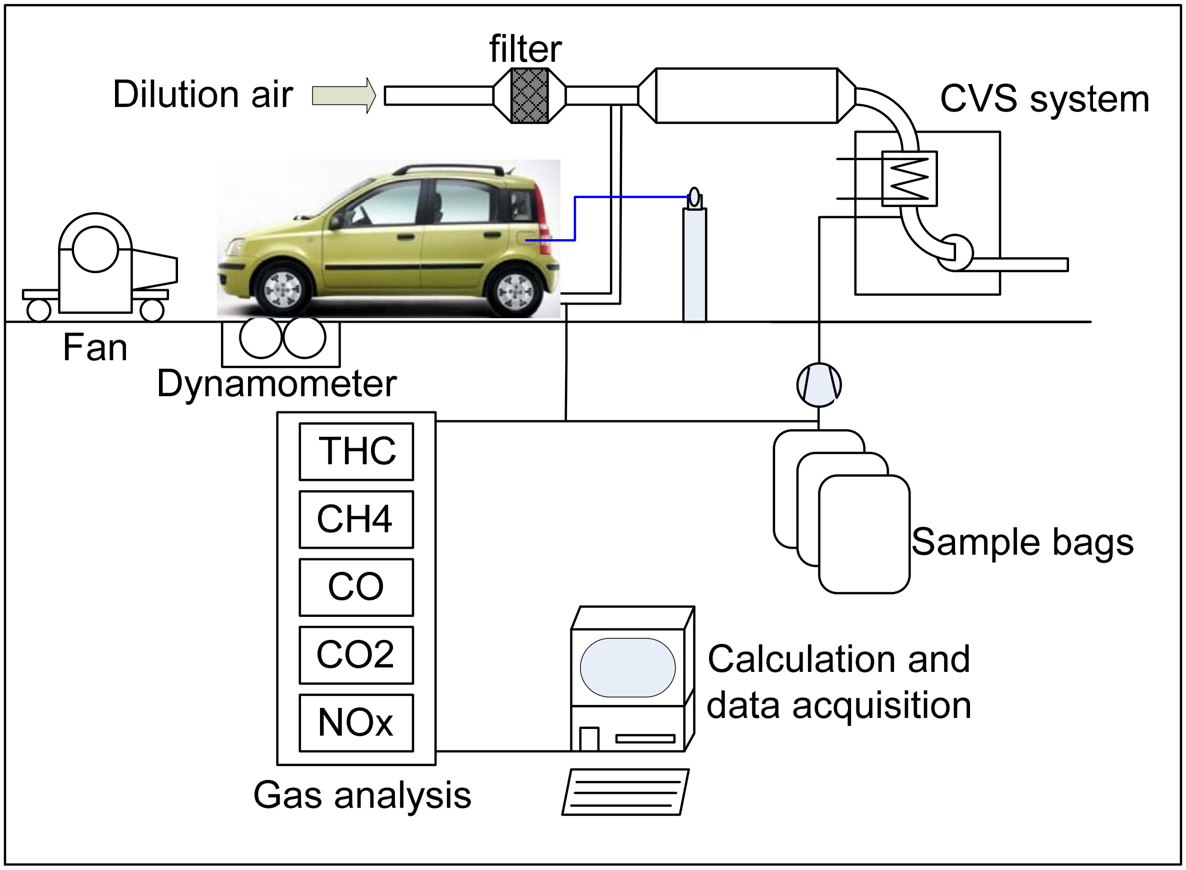

Figure 1 – Schematic diagram of test vehicle setup.

2.5 DRIVING CYCLE

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

I. quantifying as far as possible vehicle emissions under real-world driving conditions
II. assuring reproducibility and comparability of emission measurements

The testing of emissions and fuel consumption of light-duty vehicles takes place in the laboratory on chassis dynamometers. The details of the test procedure are described by Directive 98/69/EC [9] and its further amendments.

Before the emissions test, vehicles have to soak for at least 6 hours at a test temperature of 20-30°C. Emissions are then measured while vehicles follow the speed profile of the New European Driving Cycle (NEDC). The entire NEDC consists of the Urban Driving Cycle (UDC) of 780 s duration, and the Extra Urban Driving Cycle (EUDC) of 400 s duration, as presented in Figure 2.

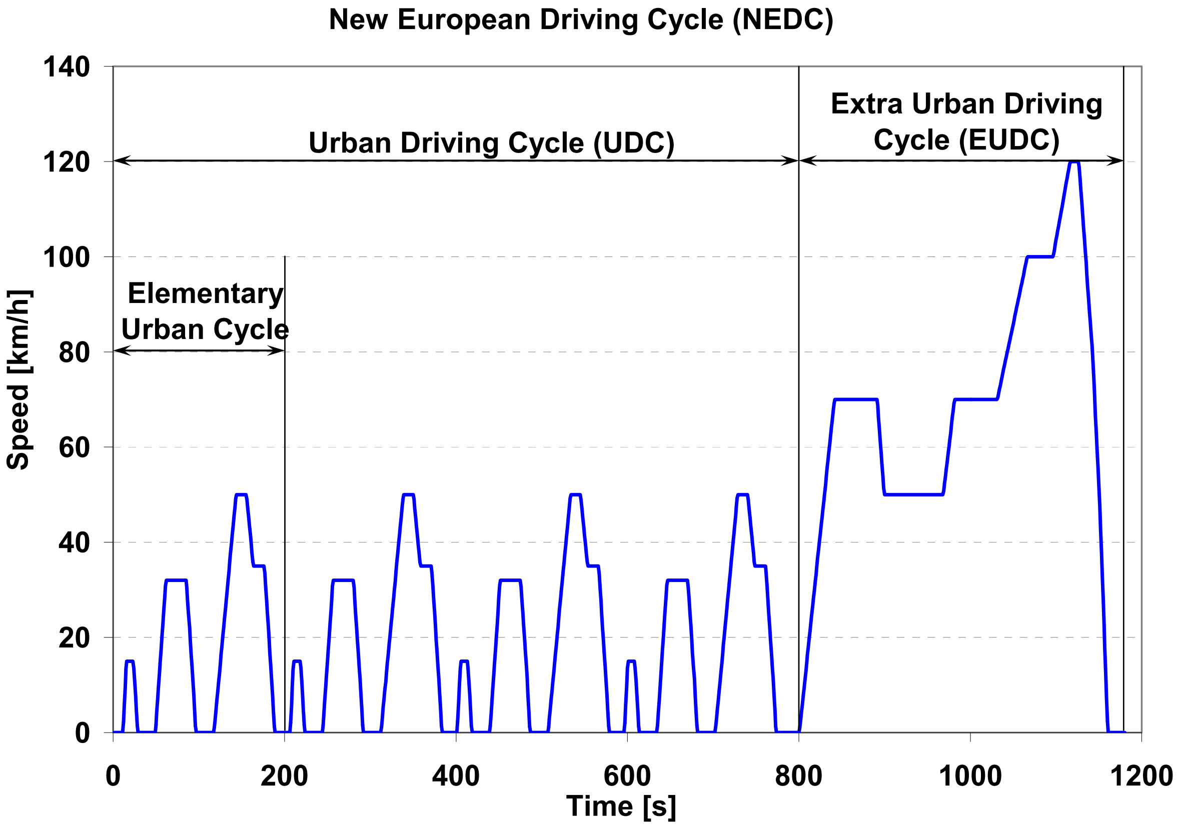

Figure 2 – New European Driving Cycle (NEDC) and its two phases: Urban Driving Cycle (EDC) and Extra Urban Driving Cycle (EUDC).

The four Elementary Urban Cycles represent urban driving conditions that are characterized by low vehicle speed, low engine load, and low exhaust gas temperature. In contrast, the EUDC accounts for extra-urban and high speed driving mode up to a maximum speed of 120 km/h. The entire NEDC covers a distance of 11,007 m in a time period of 1180 s and at an average speed of 34 km/h. An initial idling period has been eliminated in the NEDC, thus emissions sampling begins with the start of the engine. Emissions are typically sampled with a CVS system and expressed as average values over the entire test cycle in grams per kilometer [g/km] for each of the regulated pollutants. Table 4 presents the main characteristics of the NEDC.

Table 4: Specifications of individual parts of New European Driving Cycle.

Specification	Unit	ECE	EUDC
Duration	s	780	400
Average speed	km/h	19.5	62.7
Maximum speed	km/h	50	120
Length	km	4.05	6.96
Time at idle	%	29.9	10

The NEDC was developed to assure comparability and reproducibility of vehicle emissions that have been tested at standard conditions. Such an approach to emissions testing comes inevitable with limitations regarding the ability to reproduce actual on-road emissions. Criticism of the NEDC refers in particular to its smooth acceleration profile as reported by André and Pronello [15] that requires only a very narrow range of possible engine operation points [16].

3 CALCULATIONS

For obvious reasons the calculations of the unburned HC density and fuel consumption formula for the different mixtures (blends) with H_2 needs to be adapted from the regulatory ones in order to take into consideration the inclusion of H_2 in the fuel blend. Moreover, when the CNG G25 is used as basic CNG fuel, the N_2 containing in the fuel does not participate in the combustion process. The fuel consumption is expressed in m^3/100 km in the case of CNG and H_2-CNG, while for gasoline fuel it is expressed in terms of l/100 km. In order to compare the fuel consumption using a common basis, the energy consumption was calculated, in terms of MJ/100 km. To this respect, the calculation of the Higher Heating Value (HHC) as well as of the Lower Heating Value (LHV) of each fuel was deemed necessary.

3.1 HC DENSITY AND FUEL CONSUMPTION

Calculations of Fuel consumption and HC density.

For a fuel composition $C_xH_yO_z$ the factor X of the dilution factor equation is as follows:

$$X = 100 \times \frac{x}{x + \frac{y}{2} + 3.76 \times \left(x + \frac{y}{4} - \frac{z}{2} \right)} \tag{1}$$

Where: x: atoms of Carbon / mol fuel, y: atoms of H / mol fuel, and z: atoms of O / mol fuel.

Table 5 gives the nominal moles of CH_4, H_2 and N_2 of each mol of CNG fuels:

Table 5: Moles of CH_4, H_2 and N_2 of each mol of fuel.

Fuel name/type	**Moles CH_4 / mol fuel**	**Moles H_2 / mol fuel**	**Moles N_2 / mol fuel**
F3: CNG G20 (JRC)	1.000	0	0
F10: CNG G25 (JRC)	0.860	0	0.140
F2: 70% CNG 30% H_2 (OEM)	0.700	0.300	0
F4: 70% CNG G20 30% H_2 (JRC)	0.700	0.300	0
F5: 75% CNG G20 25% H_2 (JRC)	0.750	0.250	0
F6: 80% CNG G20 20 %H_2 (JRC)	0.800	0.200	0
F7: 85% CNG G20 15% H_2 (JRC)	0.850	0.150	0
F8: 90% CNG G20 10%	0.900	0.100	0

H_2 (JRC)			
F9: 95% CNG G20 5% H_2 (JRC)	0.950	0.050	0
F11: 70% CNG G25 30% H_2 (JRC)	0.602	0.300	0.098
F12 75% CNG G25 25% H_2 (JRC)	0.645	0.250	0.105
F13: 80% CNG G25 20 %H_2 (JRC)	0.688	0.200	0.112
F14 85% CNG G25 15% H_2 (JRC)	0.731	0.150	0.119
F15: 90% CNG G25 10% H_2 (JRC)	0.774	0.100	0.126
F16: 95% CNG G25 5% H_2 (JRC)	0.817	0.050	0.133

Table 6 gives the atoms of Carbon (x), Hydrogen (y), Oxygen (z) and Nitrogen (n) of each mole of fuel, calculated as:

For F16: CNG G25: 95%, H_2: 5%: x= moles of CH_4 = 0.817

y = moles H_2*2 + moles CH_4*4 = 0.050*2+0.817*4 = 3.368

z = 0, since the fuel does not contain any O_2

n = moles N_2*2 = 0.133*2 = 0.266

The last column of the Table 6 gives the calculated X from equation (1).

Table 6: Atoms of Carbon (x), Hydrogen (y) Oxygen (z) and Nitrogen of each mol of fuel as well as X factor of DF.

Fuel name/type	C atoms (x) / mol fuel	H atoms (y) / mol fuel	O atoms (z) / mol fuel	N atoms (n) / mol fuel	X factor of DF
F3: CNG G20 (JRC)	1.000	4.000	0	0	9.5
F10: CNG G25 (JRC)	0.860	3.440	0	0.280	9.5
F2: 70% CNG 30% H_2 (OEM)	0.700	3.400	0	0	8.5
F4: 70% CNG G20 30% H_2 (JRC)	0.700	3.400	0	0	8.5

F5: 75% CNG G20 25% H_2 (JRC)	0.750	3.500	0	0	8.7
F6: 80% CNG G20 20 %H_2 (JRC)	0.800	3.600	0	0	8.9
F7: 85% CNG G20 15% H_2 (JRC)	0.850	3.700	0	0	9.1
F8: 90% CNG G20 10% H_2 (JRC)	0.900	3.800	0	0	9.2
F9: 95% CNG G20 5% H_2 (JRC)	0.950	3.900	0	0	9.4
F11: 70% CNG G25 30% H_2 (JRC)	0.602	3.008	0	0.196	8.4
F12 75% CNG G25 25% H_2 (JRC)	0.645	3.080	0	0.210	8.6
F13: 80% CNG G25 20 %H_2 (JRC)	0.688	3.152	0	0.224	8.8
F14 85% CNG G25 15% H_2 (JRC)	0.731	3.224	0	0.238	9.0
F15: 90% CNG G25 10% H_2 (JRC)	0.774	3.296	0	0.252	9.2
F16: 95% CNG G25 5% H_2 (JRC)	0.817	3.368	0	0.266	9.3

The atomic mass of Carbon, Hydrogen, Oxygen and Nitrogen is equal to M_c=12.0107, M_H=1.00794, M_O=15.994 and M_N=14.0067 g/mol.

Table 7 gives the mass of Carbon, Hydrogen, Oxygen and Nitrogen of each mol of fuel, as well as the total molar mass of the fuels (with and without the Nitrogen).

For F16: CNG G25: 95%, H_2: 5%: Carbon mass = [C Atoms/fuel] * M_C = 0.817*12.0107 = 9.813 g/mol fuel.

Hydrogen mass = [H Atoms/fuel] * M_H = 3.368*1.00794 = 3.395 g/mol fuel.

Nitrogen mass = [N Atoms/fuel] * M_N = 0.266*14.0067 = 3.736 g/mol fuel.

Total molar mass = 9.813+3.395+3.736 = 16.933 g/mol fuel.

Total molar mass without Nitrogen= 9.813+3.395 = 13.207 g/mol fuel.

Table 7: Mass of Carbon, Hydrogen, Oxygen and Nitrogen of each mol of fuel, molar mass of each fuel (with and without Nitrogen).

Fuel name/type	Carbon [g/mol fuel]	Hydrogen [g/mol fuel]	Oxygen [g/mol fuel]	Nitrogen [g/mol fuel]	Molar mass [g/mol]	Molar mass (without N_2) [g/mol]
F3: CNG G20 (JRC)	12.011	4.032	0	0	16.042	16.042
F10: CNG G25 (JRC)	10.329	3.467	0	3.922	17.718	13.797
F2: 70% CNG 30% H_2 (OEM)	8.407	3.427	0	0	11.834	11.834
F4: 70% CNG G20 30% H_2 (JRC)	8.407	3.427	0	0	11.834	11.834
F5: 75% CNG G20 25% H_2 (JRC)	9.008	3.528	0	0	12.536	12.536
F6: 80% CNG G20 20 %H_2 (JRC)	9.609	3.629	0	0	13.237	13.237
F7: 85% CNG G20 15% H_2 (JRC)	10.209	3.729	0	0	13.938	13.938
F8: 90% CNG G20 10% H_2 (JRC)	10.810	3.830	0	0	14.640	14.640
F9: 95% CNG G20 5% H_2 (JRC)	11.410	3.931	0	0	15.341	15.341
F11: 70% CNG G25 30% H_2 (JRC)	7.230	3.032	0	2.745	13.008	10.262
F12 75% CNG G25 25% H_2 (JRC)	7.747	3.104	0	2.941	13.793	10.851
F13: 80% CNG G25 20 %H_2 (JRC)	8.263	3.177	0	3.138	14.578	11.440
F14 85% CNG G25 15% H_2	8.780	3.250	0	3.334	15.363	12.029

(JRC)						
F15: 90% CNG G25 10% H_2 (JRC)	9.296	3.322	0	3.530	16.148	12.618
F16: 95% CNG G25 5% H_2 (JRC)	9.813	3.395	0	3.726	16.933	13.207

Since the N_2 containing in the fuel does not participate in the combustion process, all the calculation that follow do not take into account the N_2 content of the fuel. This is also valid for the molar mass of the fuel, which was presented in the last column of Table 7 (without N_2).

The density of each fuel is calculated from the ideal gas equation, as follows (in g/l):

$$d = \frac{P \times M}{R \times T} \tag{2}$$

Where: P is the pressure (101325 Pa),

M is the molar mass of each fuel without the N_2 (in g/mol) (shown in the last column of Table 7

R is the ideal gas constant (8.314472 J/mol*K)

T is the temperature (288.15 K or 15°C)

In order to calculate the HC mass emitted as by-product due to incomplete combustion, the HC density has to be defined for each fuel. It is assumed that the unburned HC at the exhaust has the same composition as the fuel. In the case where the fuel does not contain N_2, this assumption is correct. In this case the fuel and the unburned HC have a general formula C_xH_y. The molar mass of the fuel depends on the x and y, as presented and calculated in Table 6. The HC density is calculated by the equation (2) also, but the temperature should be at 0°C (i.e. 273.15 K).

If the fuel contains also N_2 (G25), the general formula of the fuel could be expressed as $C_xH_yN_n$. But the unburned HC in the exhaust gas produced by the incomplete combustion would not contain N_2. For each mol of fuel $C_xH_yN_n$ it is assumed that the HC is produced due to incomplete combustion of a fuel having a general formula C_xH_y. In order to calculate the density of the unburned HC the molar mass of the part of the fuel without the N_2 is assumed.

Over the next part the calculation of the Fuel Consumption formula is presented. The non-stoichiometric combustion equation of a general fuel $C_xH_yO_z$ could be expressed as:

$$\begin{aligned} & a \times C_x H_y O_z + b \times O_2 + c \times N_2 \rightarrow \\ & d \times CO + e \times CO_2 + f \times HC + g \times H_2O + h \times N_2 \end{aligned} \tag{3}$$

The fuel consumption (FC) by the carbon balance would be:

$$a \times \frac{x \times M_C}{x \times M_C + y \times M_H + z \times M_O} = \\ d \times \frac{M_C}{M_{CO}} + e \times \frac{M_C}{M_{CO_2}} + f \times \frac{x \times M_C}{x \times M_C + y \times M_H + z \times M_O} \quad (4)$$

In equation (4) the M_i are the molar masses of each species. As mentioned above, the unburned HC is assumed to have the same composition as the fuel, but without N_2 in case of G25 fuels, as the N_2 does not participate in the combustion process.

Defining the Carbon Mass Fraction (CMF) as:

$$CMF = \frac{x \times M_C}{x \times M_C + y \times M_H + z \times M_O} \quad (5)$$

Equation (4) becomes as follows:

$$a \times CMF = f \times CMF + 0.429 \times d + 0.237 \times e \quad (6)$$

Where α, f, d and e are expressed in g/km

The fuel consumption α could be expressed in l/km as follows:

$$a = \frac{1}{D \times CMF} \times \left(f \times CMF + 0.429 \times d + 0.237 \times e \right) \quad (7)$$

Where D is the density of the fuel in kg/l for liquid fuels and g/l for gaseous fuels. The density of the fuel used in equation (7) (calculated by equation (2)) does not contain the N_2 of the fuel, as shown in the following Table 8. For gaseous fuels the FC or (α) in terms of m^3/100km could be expressed as follows:

$$FC\left[\frac{m^3}{100km}\right] = \frac{1}{D\left[\frac{g}{l}\right] \times CMF} \times \\ \left(f \times CMF + 0.429 \times d + 0.237 \times e \right)\left[\frac{g}{km}\right] \times 10^{-3}\left[\frac{m^3}{l}\right] \times 100 \quad (8)$$

The final equation could be expressed as:

$$FC\left[\frac{m^3}{100km}\right] = \frac{1}{10 \times D\left[\frac{g}{l}\right] \times CMF} \times \\ \left(f \times CMF + 0.429 \times d + 0.237 \times e \right)\left[\frac{g}{km}\right] \times 1\left[\frac{m^3}{l}\right] \quad (9)$$

The Carbon Mass Fraction is calculated by equation (5), with x, y and z presented in Table 6.

Table 8 presents the fuel density (D), the unburned HC density and the CMF calculated for the gaseous fuels of the study.

Table 8: Fuel density (at 288.15 K), unburned HC density (at 273.15 K, without the N_2 of fuel) and Carbon mass fraction for the tested gaseous fuels.

Fuel name/type	**Fuel density [g/l]**	**Unburned HC density [g/l]**	**Carbon mass fraction (CMF)**
F3: CNG G20 (JRC)	0.6785	0.716	0.749
F10: CNG G25 (JRC)	0.5835	0.616	0.749
F2: 70% CNG 30% H_2 (OEM)	0.5005	0.528	0.710
F4: 70% CNG G20 30% H_2 (JRC)	0.5005	0.528	0.710
F5: 75% CNG G20 25% H_2 (JRC)	0.5302	0.559	0.719
F6: 80% CNG G20 20 %H_2 (JRC)	0.5598	0.591	0.726
F7: 85% CNG G20 15% H_2 (JRC)	0.5895	0.622	0.732
F8: 90% CNG G20 10% H_2 (JRC)	0.6192	0.653	0.738
F9: 95% CNG G20 5% H_2 (JRC)	0.6488	0.684	0.744
F11: 70% CNG G25 30% H_2 (JRC)	0.4340	0.458	0.705
F12 75% CNG G25 25% H_2 (JRC)	0.4589	0.484	0.714
F13: 80% CNG G25 20 %H_2 (JRC)	0.4838	0.510	0.722
F14 85% CNG G25 15% H_2 (JRC)	0.5088	0.537	0.730
F15: 90% CNG G25 10% H_2 (JRC)	0.5337	0.563	0.737
F16: 95% CNG G25 5% H_2 (JRC)	0.5586	0.589	0.743

In Annex III the proposed formulas for reviewing the Commission Regulation (EC) No 692/2008 [7] are presented.

3.2 HEATING VALUE

In order to calculate the higher and lower heating value of each fuel, the absolute value of the enthalpy of combustion (h_c) must be calculated. Below the step by step calculation of the fuel F16 (CNG G25: 95% H_2: 5%) is given:

The stoichiometric combustion of 1 mol of this fuel could be expressed as follows:

$$\begin{aligned}&0.817\times CH_4+0.05\times H_2+0.133\times N_2+a_{th}\times\left(O_2+3.76\times N_2\right)\rightarrow\\&e\times CO_2+g\times H_2O+h\times N_2\end{aligned}\tag{10}$$

Carbon balance: $0.817=e\Rightarrow e=0.817$

Hydrogen balance: $0.817\times 4+0.05\times 2=2\times g\Rightarrow g=1.684$

Oxygen balance: $2\times a_{th}=2\times e+g\Rightarrow 2\times a_{th}=2\times 0.817+1.684\Rightarrow a_{th}=1.659$

Nitrogen balance: $0.133\times 2+2\times a_{th}\times 3.76=2\times h\Rightarrow h=0.133+3.76\times 1.659\Rightarrow h=6.37084$

The stoichiometric air/fuel ratio could be calculated as follows:

$$\left({}^{A}\!/\!_{F}\right)_{st}=\frac{m_{air}}{m_{fuel}}=\frac{mol_O\times M_O+mol_N\times M_N}{mol_C\times M_C+mol_H\times M_H+mol_N\times M_N}\tag{11}$$

For fuel F16 (CNG G25: 95% H_2: 5%): Replacing in equation (11) we obtain:

$$\left({}^{A}\!/\!_{F}\right)_{st}=\frac{2\times a_{th}\times M_O+2\times 3.76\times a_{th}\times M_N}{0.817\times M_C+(0.817\times 4\times 0.05\times 2)\times M_H+0.133\times 2\times M_N}\Rightarrow$$

$$\left({}^{A}\!/\!_{F}\right)_{st}=\frac{2\times 1.659\times 15.9994+2\times 3.76\times 1.659\times 14.0067}{0.817\times 12.0107+(0.817\times 4\times 0.05\times 2)\times 1.00794+0.133\times 2\times 14.0067}\Rightarrow$$

$$\left({}^{A}\!/\!_{F}\right)_{st}=13.455$$

Table 9 provides the theoretic air constant (α_{th}), the products' constants and the air/fuel ratio for the stoichiometric combustion of the gaseous fuels tested.

Table 9: Theoretic constant of air in the combustion (α_{th}) and constants e, g, h of the products for the tested gaseous fuels.

Fuel name/type	Air constant α_{th}	CO_2 constant e	H_2O constant g	N_2 constant h	$(A/F)_{st}$
F3: CNG G20 (JRC)	2.000	1.000	2.000	7.520	17.121
F10: CNG G25 (JRC)	1.660	0.860	1.600	6.382	12.866
F2: 70% CNG 30% H_2 (OEM)	1.550	0.700	1.700	5.828	17.986
F4: 70% CNG G20 30% H_2 (JRC)	1.550	0.700	1.700	5.828	17.986
F5: 75% CNG G20 25% H_2 (JRC)	1.625	0.750	1.750	6.110	17.802
F6: 80% CNG G20 20 %H_2 (JRC)	1.700	0.800	1.800	6.392	17.637
F7: 85% CNG G20 15% H_2 (JRC)	1.775	0.850	1.850	6.674	17.488
F8: 90% CNG G20 10% H_2 (JRC)	1.850	0.900	1.900	6.956	17.354
F9: 95% CNG G20 5% H_2 (JRC)	1.925	0.950	1.950	7.238	17.232
F11: 70% CNG G25 30% H_2 (JRC)	1.354	0.602	1.504	5.189	14.295
F12 75% CNG G25 25% H_2 (JRC)	1.415	0.645	1.540	5.425	14.089
F13: 80% CNG G25 20 %H_2 (JRC)	1.476	0.688	1.576	5.662	13.904
F14 85% CNG G25 15% H_2 (JRC)	1.537	0.731	1.612	5.898	13.739

F15: 90% CNG G25 10% H_2 (JRC)	1.598	0.774	1.648	6.134	13.590
F16: 95% CNG G25 5% H_2 (JRC)	1.659	0.817	1.684	6.371	13.455

Table 10 gives the enthalpies of formation (h_f) for the chemical compounds that participate to the combustion process. The Higher Heating Value (HHV) is calculated assuming the water in liquid phase in the products, while in the Lower Heating Value (LHV) the water is in gas phase.

Table 10: Enthalpies of formation for CH_4, CO_2, $H_2O_{(g)}$, $H_2O_{(l)}$, O_2, N_2, H_2 at 1 atm and 298.15 K (25°C).

Chemical compound	**Chemical formula**	**Enthalpy of formation (h_f in kJ/mol)**
Methane	CH_4	-74.87
Carbon dioxide	CO_2	-393.5
Water (gas phase)	$H_2O_{(g)}$	-241.82
Water (liquid phase)	$H_2O_{(l)}$	-285.8
Oxygen	O_2	0
Nitrogen	N_2	0
Hydrogen	H_2	0

For fuel F16 (CNG G25: 95% H_2: 5%), assuming the water in liquid phase in the products, the enthalpy of combustion (h_c) is calculated as follows:

$$h_c = \sum h_{f(pro)} - \sum h_{f(reac)} \tag{12}$$

The enthalpies of O_2, N_2, and H_2 do not participate, since their value is zero. From equations (10) and (12) we obtain:

$$h_c = e \times h_{f(CO_2)} + g \times h_{f\left(H_2O_{(l)}\right)} - 0.817 \times h_{f(CH_4)} \Rightarrow$$

$$h_c = 0.817[mol] \times \left(-393.5\left[\frac{kJ}{mol}\right]\right) + 1.684[mol] \times \left(-285.8\left[\frac{kJ}{mol}\right]\right) - 0.817[mol] \times \left(-74.87\left[\frac{kJ}{mol}\right]\right) \Rightarrow$$

$$h_c = -741.608\left[\frac{kJ}{molfuel}\right]$$

The HHV is the absolute value of the enthalpy of combustion, or 741.608 kJ/mol fuel. If the enthalpy of formation of water in gas phase would be used (-241.82 kJ/mol, Table 10), the LHV could be calculated for the specific fuel, with value 667.546 kJ/mol fuel.

The heating value of gaseous fuels could be also expressed in terms of MJ/m^3 (divided by molar mass of fuel – Table 7 and multiplied by the fuel density – Table 8):

$$HHV_{gf} = 741.608\left[\frac{kJ}{mol}\right]\times\frac{1}{13.207}\left[\frac{mol}{g}\right]\times 0.5586\left[\frac{g}{l}\right]\times 10^{-3}\left[\frac{MJ}{kJ}\right]\times 10^{3}\left[\frac{l}{m^3}\right] = 31.36445\left[\frac{MJ}{m^3}\right]$$

$$LHV_{gf} = 667.542\left[\frac{kJ}{mol}\right]\times\frac{1}{13.207}\left[\frac{mol}{g}\right]\times 0.5586\left[\frac{g}{l}\right]\times 10^{-3}\left[\frac{MJ}{kJ}\right]\times 10^{3}\left[\frac{l}{m^3}\right] = 28.23217\left[\frac{MJ}{m^3}\right]$$

Table 11 presents the HHV and LHV of the gaseous fuels participating in the study.

Table 11: Higher Heating Value (HHV) and Lower Heating Value (LHV) in terms of kJ/mol and MJ/m^3 of the tested gaseous fuels.

Fuel name/type	HHV [kJ/mol fuel]	LHV [kJ/mol fuel]	HHV [MJ/m^3 fuel]	LHV [MJ/m^3 fuel]
F3: CNG G20 (JRC)	890.230	802.270	37.6500	33.9300
F10: CNG G25 (JRC)	731.302	660.934	30.9286	27.9525
F2: 70% CNG 30% H_2 (OEM)	708.901	634.135	29.9812	26.8192
F4: 70% CNG G20 30% H_2 (JRC)	708.901	634.135	29.9812	26.8192
F5: 75% CNG G20 25% H_2 (JRC)	739.123	662.158	31.2593	28.0043
F6: 80% CNG G20 20 %H_2 (JRC)	769.344	690.180	32.5375	29.1894
F7: 85% CNG G20 15% H_2 (JRC)	799.566	718.203	33.8156	30.3746
F8: 90% CNG G20 10% H_2 (JRC)	829.787	746.225	35.0938	31.5597
F9: 95% CNG G20 5% H_2 (JRC)	860.009	774.248	36.3719	32.7449
F11: 70% CNG G25 30% H_2 (JRC)	621.658	555.513	26.2915	23.4940
F12 75% CNG G25 25% H_2 (JRC)	645.648	577.919	27.3061	24.4416

F13: 80% CNG G25 20 %H_2 (JRC)	669.638	600.326	28.3207	25.3893
F14 85% CNG G25 15% H_2 (JRC)	693.628	622.732	29.3353	26.3369
F15: 90% CNG G25 10% H_2 (JRC)	717.618	645.139	30.3499	27.2845
F16: 95% CNG G25 5% H_2 (JRC)	741.608	667.546	31.3644	28.2322

The HHV and LHV of gasoline fuel E0 is 45.433 and 42.358 MJ/kg respectively. Divided by the density, the HHV and LHV are obtained in terms of MJ/l:

$$HHV_{E0} = 45.433\left[\frac{MJ}{kg}\right]\times 0.747\left[\frac{kg}{l}\right] = 34.76239\left[\frac{MJ}{l}\right]$$

$$LHV_{E0} = 42.358\left[\frac{MJ}{kg}\right]\times 0.747\left[\frac{kg}{l}\right] = 32.45566\left[\frac{MJ}{l}\right]$$

The calculated fuel consumption of each fuel could be transformed in terms of Energy Consumption (EC) expressed in MJ/100km as follows:

For liquid fuel E0: $EC_{E0}\left[\frac{MJ}{100km}\right] = FC\left[\frac{l}{100km}\right]\times LHV_{E0}\left[\frac{MJ}{l}\right]$

For gaseous fuels: $EC_{gf}\left[\frac{MJ}{100km}\right] = FC\left[\frac{m^3}{100km}\right]\times LHV_{gf}\left[\frac{MJ}{m^3}\right]$

4 RESULTS

4.1 BAG GASEOUS EMISSIONS

4.1.1 TOTAL HYDROCARBON EMISSIONS

Figure 3 depicts the emissions of hydrocarbons from the different blends as well as the reference (benchmark) fuel i.e. CNG. It also shows the measured emission when the vehicle was tested with petrol and also the emission variation due to the ambient temperature of the tests with petrol. In all the cases the vehicle complies with the regulated limits. It is worthwhile to indicate that there is a positive trend of THC reduction as the hydrogen concentration increases as expected by the reduction of CH_4 in the fuel. The emissions over the NEDC are dominated by the emissions over the cold-start UDC part of the cycle. The emissions over the EUDC remain at very low levels, since the warmed-up TWC oxidizes effectively the HC.

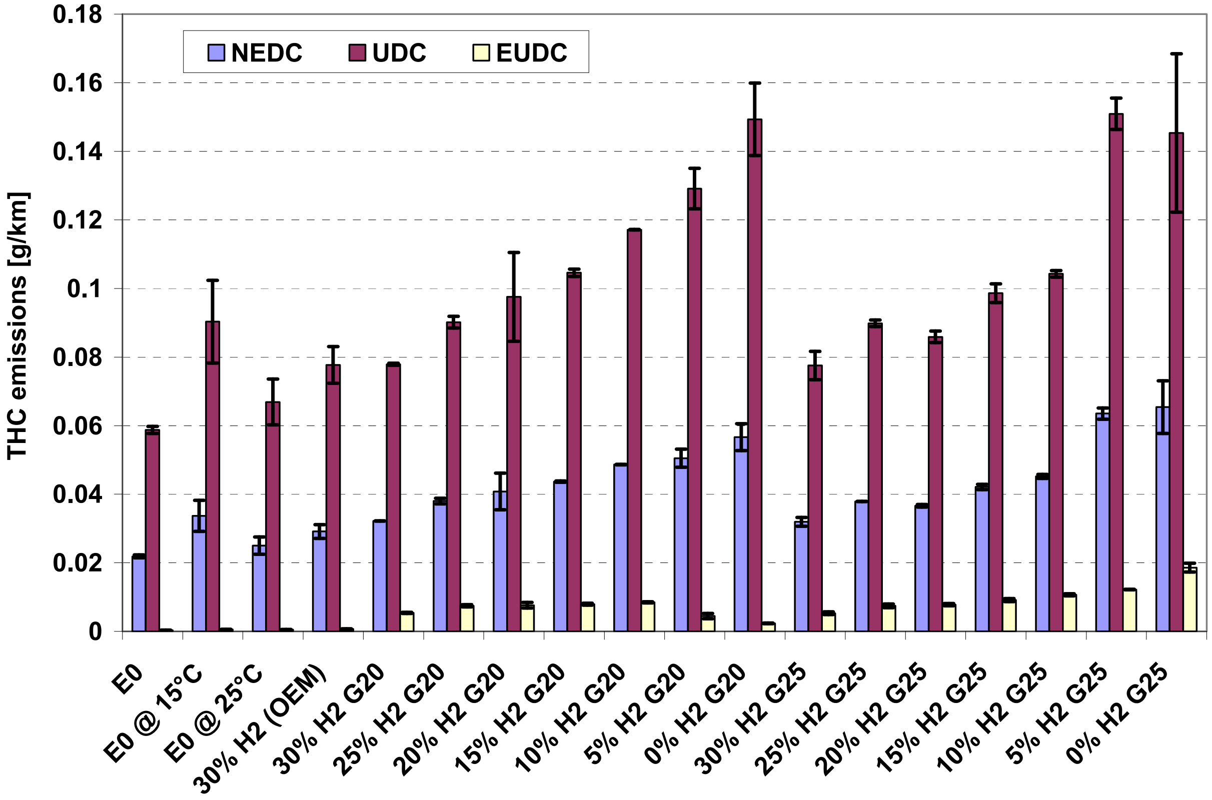

Figure 3 – Total HC emissions for the vehicle tested running on the various fuels of the study over the NEDC, UDC and EUDC.

4.1.2 NON-METHANE HYDROCARBON EMISSIONS

Figure 4 depicts the emissions of Non-Methane Hydrocarbons (NMHC) from the different blends as well as the reference (benchmark) fuel i.e. CNG. It also shows the measured emission when the vehicle was tested with petrol and also the emission variation due to the ambient temperature of the tests with petrol. No regulated limits of NMHC emissions were applicable to Euro 4 emission standards. The NMHC emissions were firstly regulated for vehicles equipped with PI engines with the introduction of the Euro 5/6 emission standards. However, in all the cases the vehicle complies with those regulated limits, although it is based on a Euro 4 certified model. It is worthwhile to indicate that as it could be expected most of the emissions are of the methane type as the fuel is mainly CH_4. This is evident by the almost double NMHC emissions of the vehicle while running on petrol fuel (E0). The emitted NMHC emissions of the vehicle when operating on CNG blends was measured only over the UDC part of the cycle. A possible explanation could be the fact that the engine always starts on liquid petrol fuel in order to ensure a cold start without problems, even if the selected/predefined fuel is the gaseous (CNG). After some seconds of operation on petrol the engine switches automatically its operation on the gaseous fuel. The outlier for the case of 10% H_2 in CNG (G25) was due to a malfunctioning of the measuring device in that experimental day/fuel, where no CH_4 emissions measurement was done.

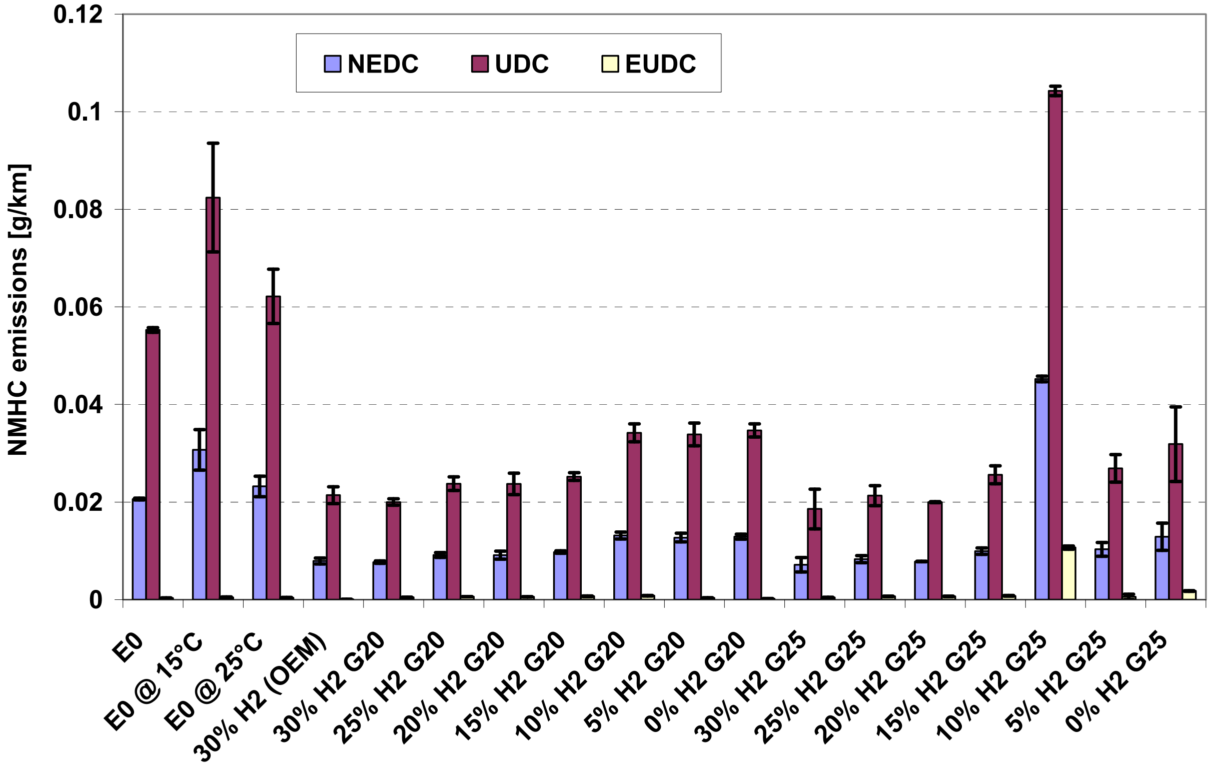

Figure 4 – NMHC emissions for the vehicle tested running on the various fuels of the study over the NEDC, UDC and EUDC.

4.1.3 CARBON MONOXIDE EMISSIONS

Figure 5 depicts the emissions of CO from the different blends as well as the reference (benchmark) fuel i.e. CNG. It also shows the measured emission when the vehicle was tested with petrol and also the emission variation due to the ambient temperature of the tests with petrol. In all the cases the vehicle complies with the regulated limits. It is worthwhile to indicate that as in the case of THC there is a (non-monotonic) trend in the positive reduction of CO emissions as the hydrogen concentration increases, that it could be attributed to the reduction of CH_4 in the fuel.

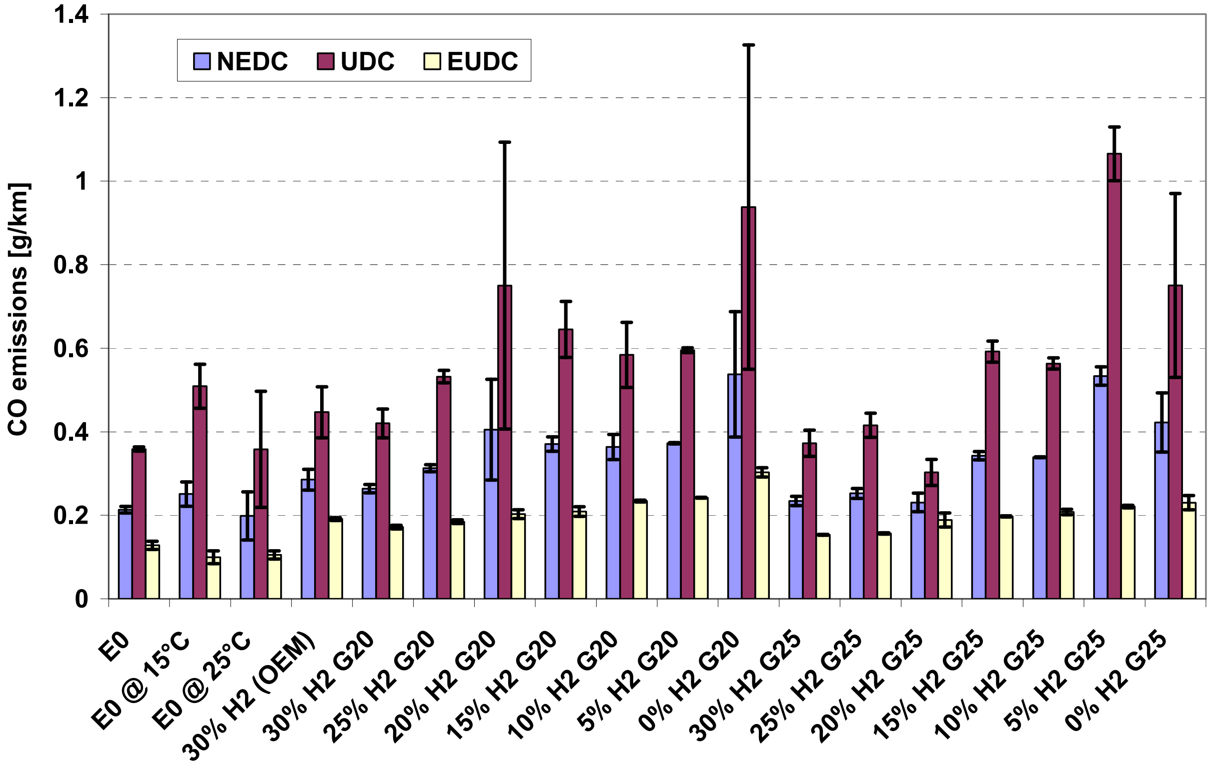

Figure 5 – CO emissions for the vehicle tested running on the various fuels of the study over the NEDC, UDC and EUDC.

4.1.4 NITROGEN OXIDES EMISSIONS

Figure 6 depicts the emissions of NO_x from the different blends as well as the reference (benchmark) fuel i.e. CNG. It also shows the measured emission when the vehicle was tested with petrol and also the emission variation due to the ambient temperature of the tests with petrol. In all the cases the vehicle complies with the regulated limits. It is worthwhile to indicate that there is a trend on NO_x emission increase as the hydrogen concentration increases. This can be explained because as the hydrogen concentration increases the combustion temperature also increases [17]. As consequence, more nitrogen in the air can be burnt therefore increasing the engine-out NO_x emissions. However, this may be one of the possible explanations, since no engine-out emissions were measured during this experimental campaign. Other factors may also affect the NO_x engine-out emissions that were not monitored (e.g. the ignition timing, the burned gas fraction in the in-cylinder unburned mixture, the air/fuel ratio etc) [18].

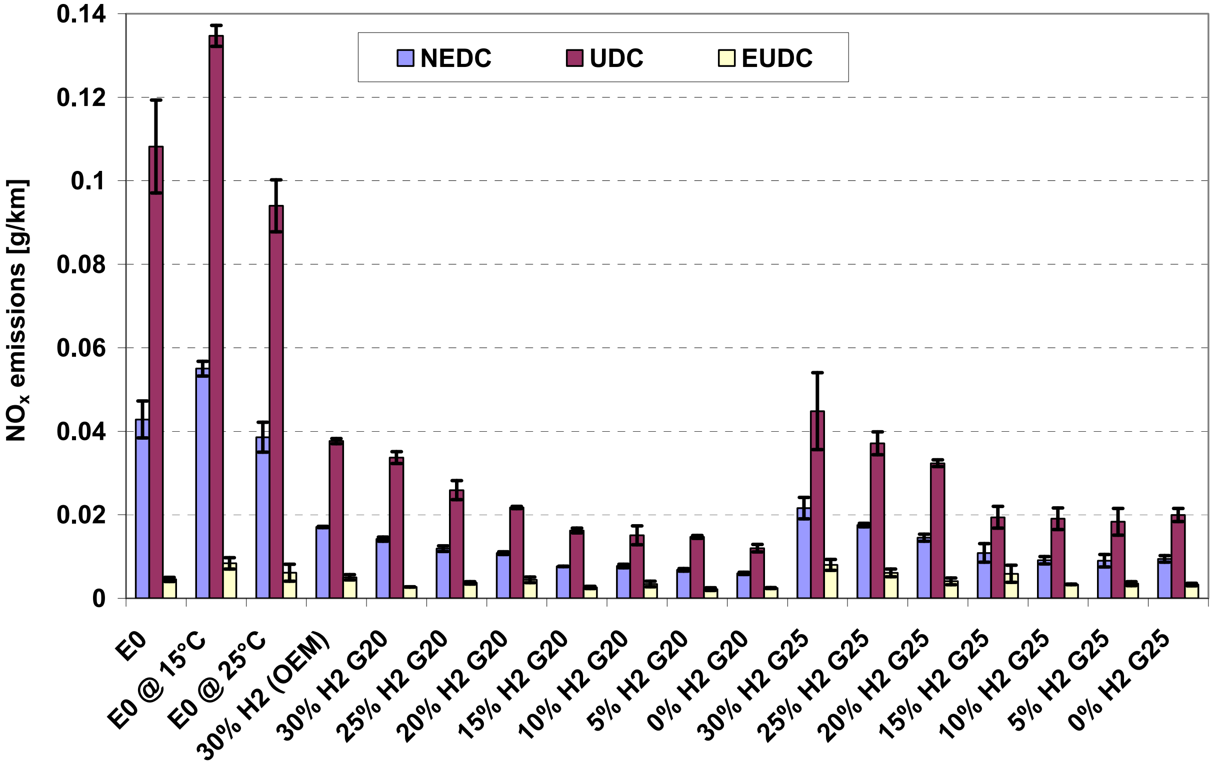

Figure 6 – NO_x emissions for the vehicle tested running on the various fuels of the study over the NEDC, UDC and EUDC.

4.1.5 CARBON DIOXIDE EMISSIONS

Figure 7 depicts the emissions of CO_2 from the different blends as well as the reference (benchmark) fuel i.e. CNG. It also shows the measured emission when the vehicle was tested with petrol and also the emission variation due to the ambient temperature of the tests with petrol. There is a clear reduction on the levels of CO_2 emissions with the increase of H_2 content in the mixture consistent with the decrease of carbon in the mixed fuel. This also indicates that the use of the H_2-CNG blends could be a valuable tool to reduce the overall contribution to the GHG emissions of transport sector.

Evident of decrease CO_2 emissions is also obvious with the petrol fuel E0, when the Type I test is conducted at 25°C, compared to the respective results at 22 or 15°C.

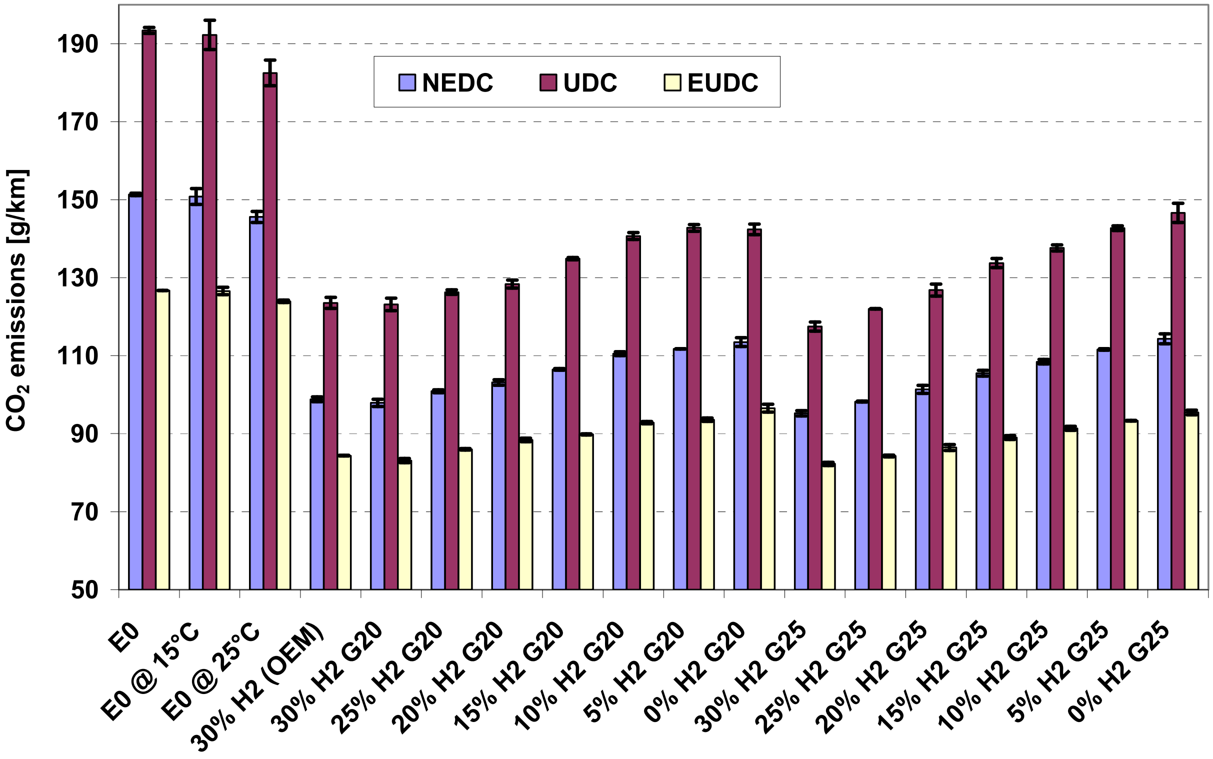

Figure 7 – CO_2 emissions for the vehicle tested running on the various fuels of the study over the NEDC, UDC and EUDC.

4.2 PARTICULATE EMISSIONS

Figure 8 and Figure 9 depict the levels of Particulate Matter (PM) and Particle Number (PN) emissions respectively. There is not a clear trend in any of the two measurements. This is due to the low levels of emissions (both at mass and particle number) that it will accompany with a large uncertainty in the data obtained from the test. More details of the PM/PN results of this vehicle can be found elsewhere [19].

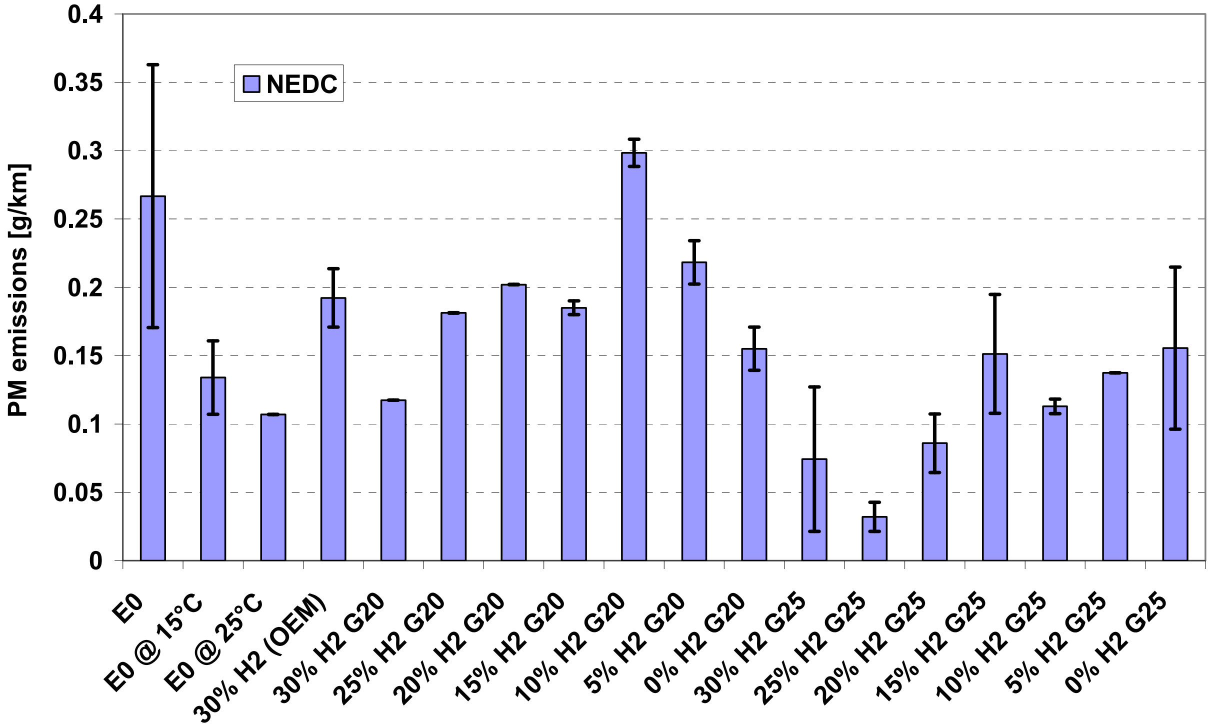

Figure 8 – PM emissions for the vehicle tested running on the various fuels of the study over the NEDC.

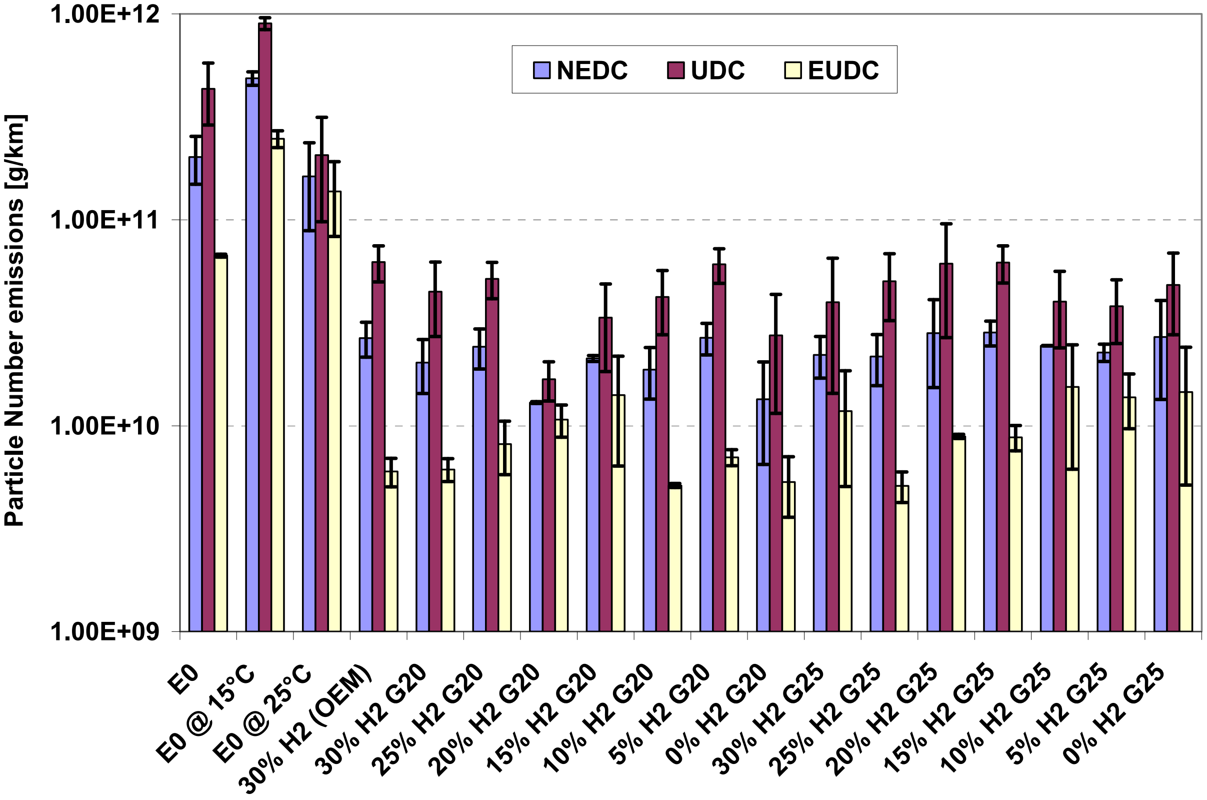

Figure 9 – PN emissions for the vehicle tested running on the various fuels of the study over the NEDC, UDC and EUDC.

4.3 FUEL/ENERGY CONSUMPTION

Figure 10 depicts the fuel consumption obtained from testing the vehicles at different levels of H_2 in the mixture H_2-CNG. For a direct comparison between the liquid and gaseous fuels the FC is expressed in terms of l/100 km for E0 and in m^3/100 km for the H_2-CNG blends. The volumetric FC of the H_2-CNG (G25) blend is higher than the respective FC values of the H_2-CNG (G20) ones, due to the higher energy content of the latter fuels, as shown in Table 11. Although this graph was produced in terms of fuel volume consumed per 100 km the appropriate way to make a reasonable comparison among the different fuels should be to compare the Energy Consumption (EC) per 100 km, as shown in Figure 11. This is because each fuel has different energy content and a mere volumetric comparison does not give a clear picture. In this case the EC is presented in terms of MJ/100 km for both gaseous and liquid fuels, and ranges between 200-210 MJ/100 km over the NEDC, for all the fuels of this study.

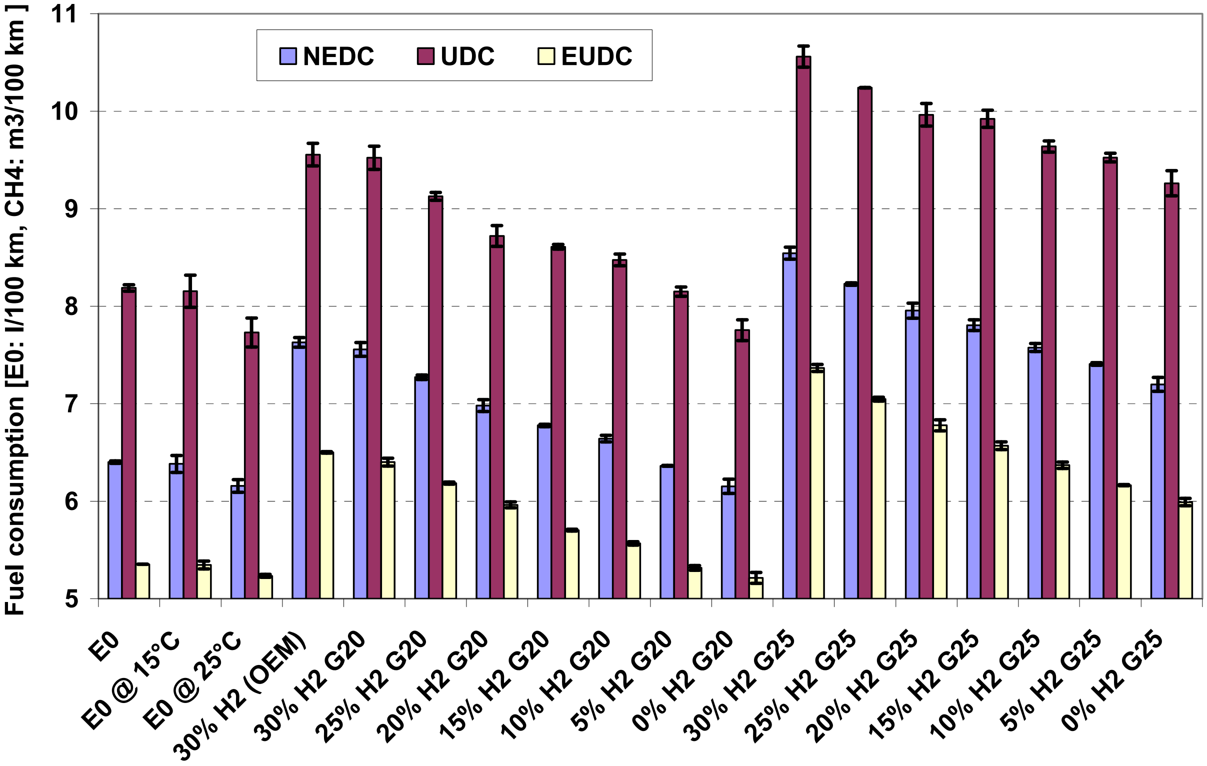

Figure 10 – Fuel consumption for the vehicle tested running on the various fuels of the study over the NEDC, UDC and EUDC.

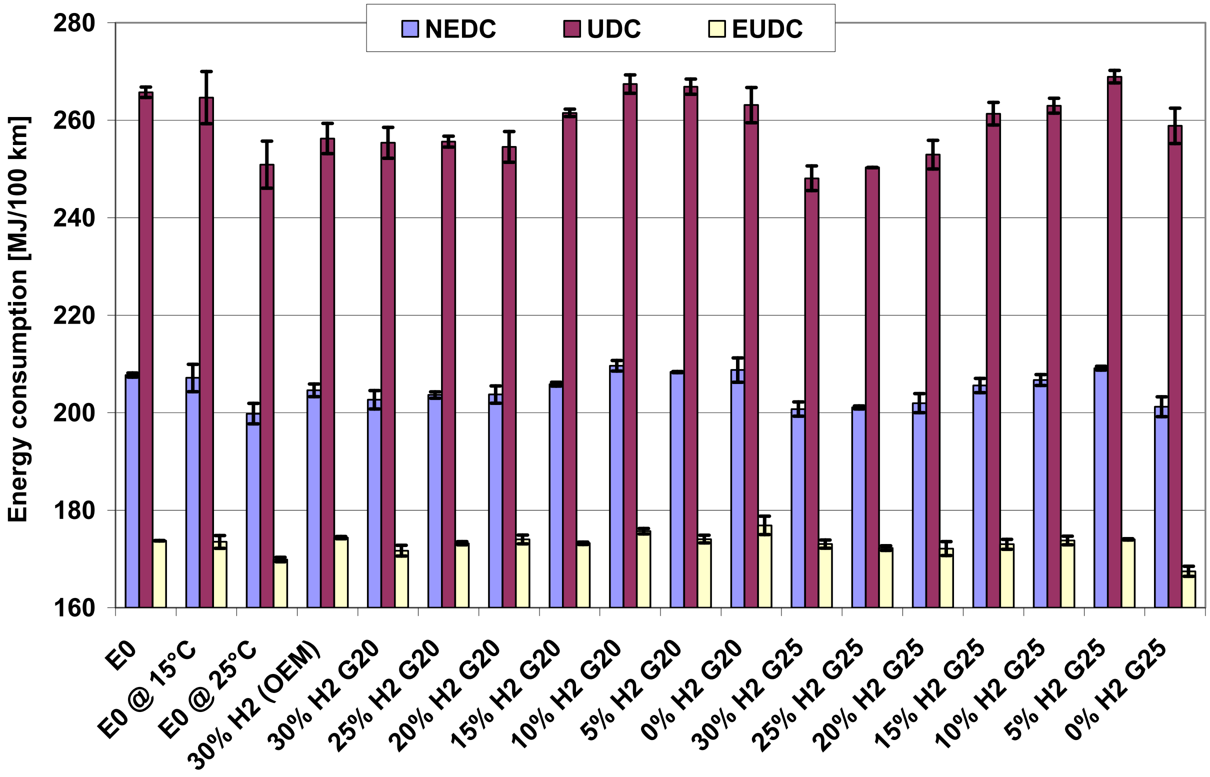

Figure 11 – Energy consumption for the vehicle tested running on the various fuels of the study over the NEDC, UDC and EUDC.

4.4 *MODAL GASEOUS EMISSIONS*

Second by second concentration of the pollutants were recorded during the regulatory cycle in order to compare with the results obtained using the bag emission tests (integration through the cycle). The figures depict the differences for all the measurements performed (at least 2 per blend).

In order to calculate the mass of each pollutant from the modal concentration, the formula below has been applied for each second of the measurement:

$$M_i\left[\frac{g}{s}\right]=\dot{V}\left[\frac{m^3}{\min}\right]\cdot d_i\left[\frac{g}{l}\right]\cdot C_i\cdot 10^3\left[\frac{l}{m^3}\right]\cdot 60^{-1}\left[\frac{\min}{s}\right] \qquad (13)$$

Where:

M_i M_i is the mass of pollutant i in g/s,

$\dot{V}$ is the exhaust flow rate in m^3/min

d_i is the density of pollutant i in g/l

C_i is the modal concentration of pollutant i

The total mass in grams over the whole driving cycle is calculated integrated in time.

Figure 12 depicts the second by second modal concentrations for CO_2, O_2, CO, total HC and NO_x, as well as the lambda value calculated by the instantaneous emissions, for one of the tests performed, over the NEDC. The CO and total HC emission performance is characterized by the cold-start effect, where the majority of them are emitted over the first seconds of the cycle, before the catalyst's light-off. The O_2 concentration remains at zero during steady-state speed driving (e.g. over the EUDC, as the engine operates at stoichiometric mode – lambda=1), while over the UDC part, some O_2 spikes are observed due to the fuel cut-off during vehicle deceleration. At the same time instants (fuel cut-off), the CO_2 concentration decreases to zero. The NO_x emission pattern is characterized by a high concentration spike over the cold-start period, probably for the same reason as for CO and total HC, while some spikes are evident over the whole UDC part, due to the simultaneous lambda spikes. Over the EUDC the NO_x concentration remains zero, probable due to the stoichiometric operation of the TWC.

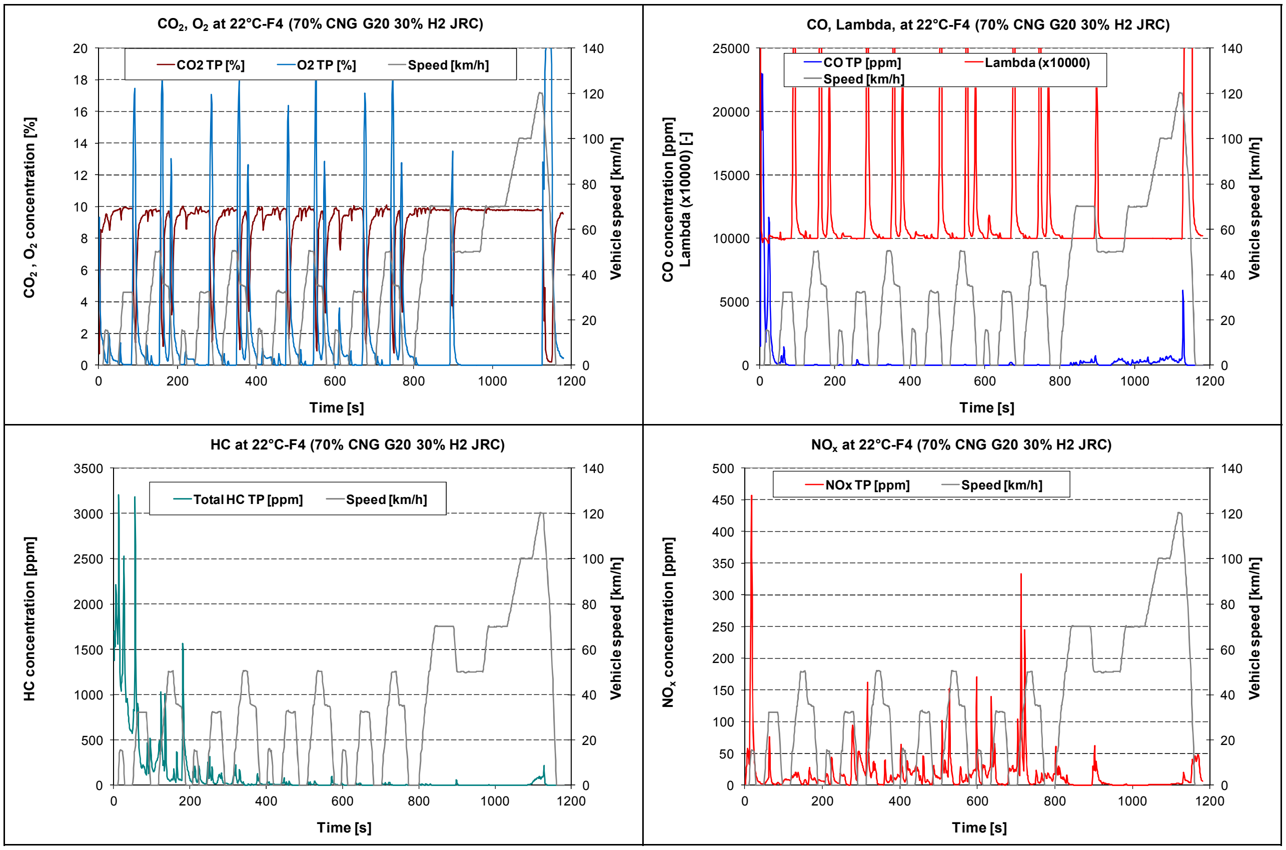

Figure 12 – Modal emissions of CO_2, O_2, CO, THC and NO_x for the vehicle tested running on the fuel F4: 70% CNG G20 30% H_2 (JRC).

Figure 13 presents the cumulative mass emissions of CO, total HC and NO_x over the NEDC of the same test, calculated according to the equation (13). It is obvious that half of the total CO emissions were emitted over the first seconds of the cycle (cold-start effect), as already discussed, while over the EUDC the CO emissions increased further. A possible explanation could be the inadequate oxidation of this pollutant in the TWC over the high flow rate – low residence time of the exhaust gas under such operating conditions. The monitoring of the engine-out modal data upstream of the TWC (not available at the specific experimental campaign) could have shed more light on such phenomena.

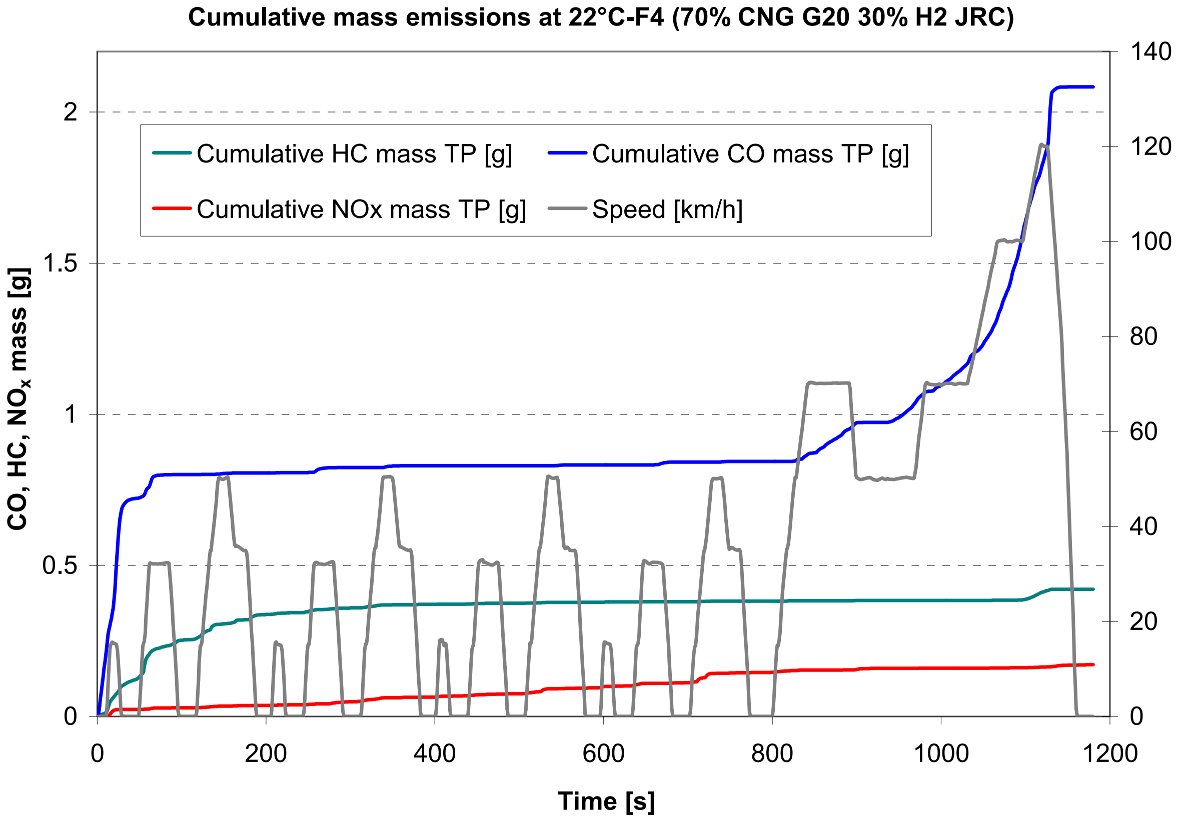

Figure 13 – Cumulative CO, total HC and NO_x mass emissions over the NEDC of a test running on fuel F4 (70% CNG G20 – 30% H_2).

4.4.1 TOTAL HYDROCARBON MODAL EMISSIONS

Figure 14 (left chart) shows the relation between the total HC emission values obtained from the bag measurements and those obtained by the "second by second" recording of on-line detectors. The agreement between both measurements is better as closer these points are to a line with slope equal to 1. Figure 14 (right chart) depicts the same values in terms of the percentage difference between both measurements. The values for H_2-CNG are of the same order of magnitude as for the petrol case (~20%). These differences can be attributed to the accuracy of the detector used for the experiments at this low values, as it is of the same order as in the case of petrol fuel (E0).

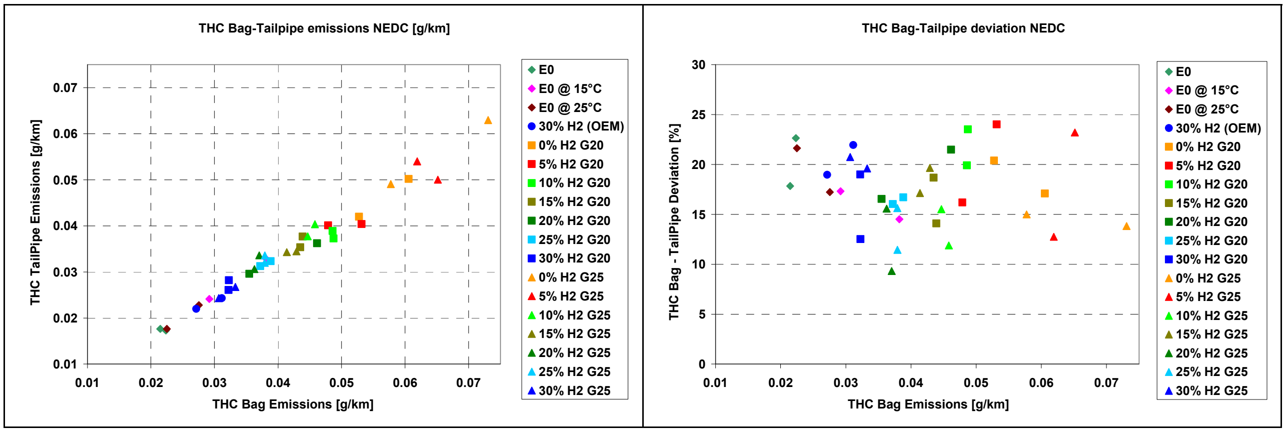

Figure 14 – Comparison in terms of mass emission values (left chart) and in terms of percentage difference (right chart) between bag and modal measurements for total HC emission.

4.4.2 *CARBON MONOXIDE MODAL EMISSIONS*

Figure 15 (left chart) shows the relation between the CO emission values obtained from the bag measurements and those obtained by the “second by second” recording of on-line detectors. The agreement between both measurements is better as closer these points are to a line with slope equal to 1. Figure 15 (right chart) depicts the same values in terms of the percentage difference between both measurements. The values for H_2-CNG are of the same order of magnitude as for the petrol case (~30%). These differences can be attributed to the accuracy of the detector used for the experiments at this low values, as it is of the same order as in the case of petrol fuel (E0).

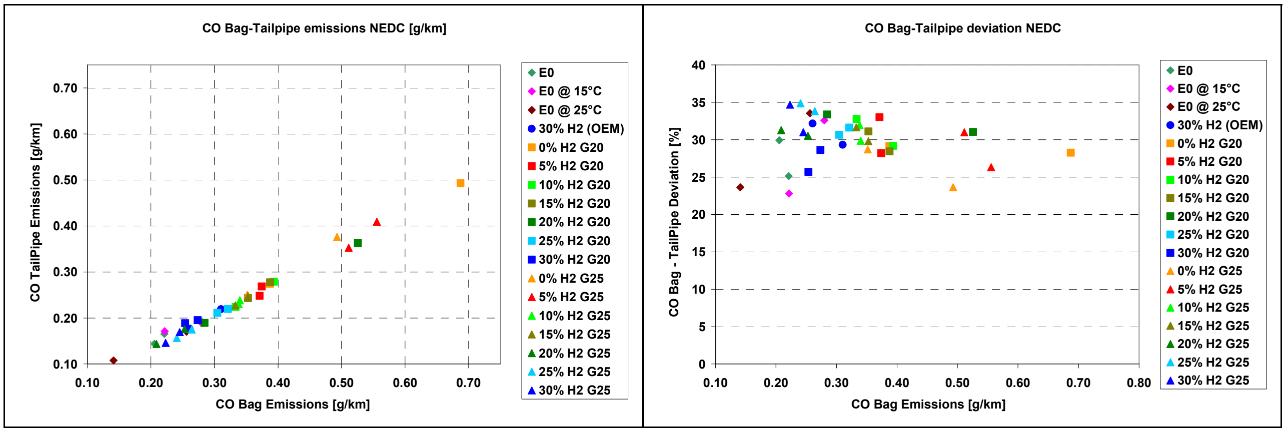

Figure 15 – Comparison in terms of mass emission values (left chart) and in terms of percentage difference (right chart) between bag and modal measurements for CO emission.

4.4.3 *NITROGEN OXIDES MODAL EMISSIONS*

Figure 16 (left chart) shows the relation between the NO_x emission values obtained from the bag measurements and those obtained by the “second by second” recording of on-line detectors. The agreement between both measurements is better as closer these points are to a line with slope equal to 1. Figure 16 (right chart) depicts the same values in terms of the percentage difference between both measurements. The values for H_2-CNG are of the same order of magnitude as for the petrol case (~10%). These differences can be attributed to the accuracy of the detector used for the experiments at this low values, as it is of the same order as in the case of petrol fuel (E0).

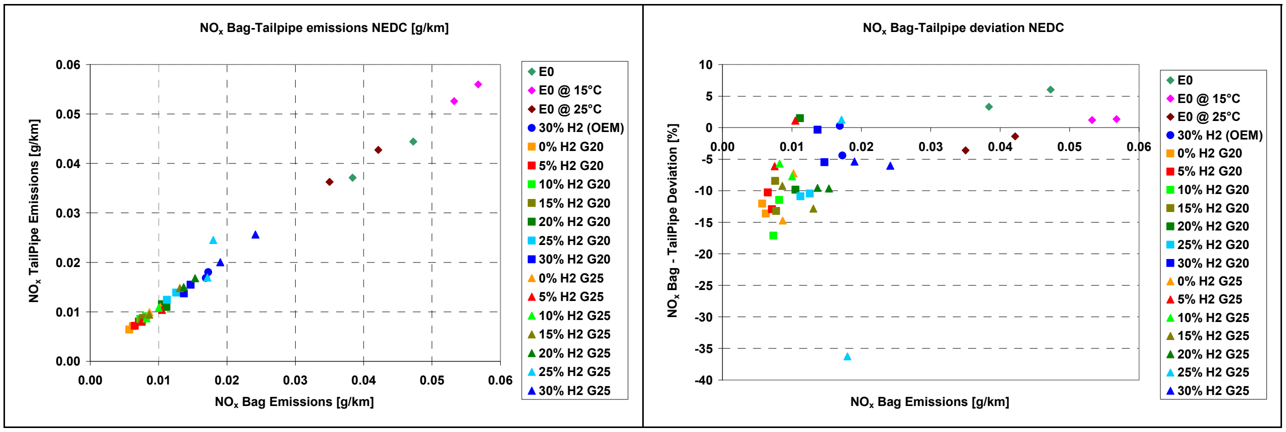

Figure 16 – Comparison in terms of mass emission values (left chart) and in terms of percentage difference (right chart) between bag and modal measurements for NO_x emission.

4.4.4 CARBON DIOXIDE MODAL EMISSIONS

Figure 17 (left chart) shows the relation between the CO_2 emission values obtained from the bag measurements and those obtained by the “second by second” recording of on-line detectors. The agreement between both measurements is better as closer these points are to a line with slope equal to 1. Figure 17 (right chart) depicts the same values in terms of the percentage difference between both measurements. The values for H_2-CNG are of the same order of magnitude as for the petrol case (<1%). These smaller differences as compared with the case of the other pollutant can be due to the larger values that were measured and therefore a better accuracy of the detector used for the experiments.

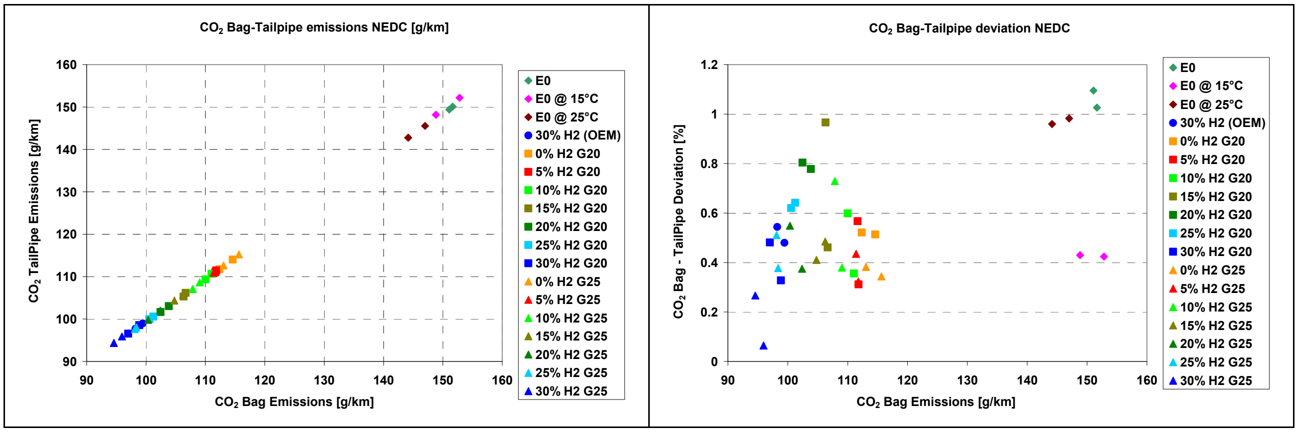

Figure 17 – Comparison in terms of mass emission values (left chart) and in terms of percentage difference (right chart) between bag and modal measurements for CO_2 emission.

5 CONCLUSIONS

This report presented the main results of an experimental campaign carried out by the JRC in support of the legislative activities of DG ENTR for the development of the Regulation (EC) No 79/2009 of the European Parliament and of the Council [3] on type-approval of hydrogen-powered motor vehicles, and amending Directive 2007/46/EC [4]. It has served as the scientific and technical basis to test the proposed methods for type approval regarding vehicles using a variable mixture of H_2 and CNG.

A prototype bi-fuel vehicle was tested, designed to operate either on petrol or on various H_2-CNG blends, with maximum percentage of 30 per cent H_2 on CNG. The methodology used to estimate the unburned hydrocarbon density, the fuel density, the fuel consumption, and the heating value of each H_2-CNG blend was given. The bag and modal gaseous emissions, as well as the particulate emission performances of the vehicle tested under the various H_2-CNG blends and on petrol fuel was presented. From the results it can be concluded that the use of such fuel mixtures can provide a positive input to the reduction of pollutant emissions as well as of GHG emissions.

6 LIST OF SPECIAL TERMS AND ABBREVIATIONS

CH_4	Methane
CMF	Carbon Mass Fraction
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CVS	Constant Volume Sampler
DG-ENTR	Directorate General Enterprise and Industry
EU	European Union
EUDC	Extra-Urban Driving Cycle (Part 2 of the NEDC driving cycle)
Euro #	European Emission Standard
GHG	Greenhouse Gas
H_2	Hydrogen
HC	Hydrocarbon
HHV	Higher Heating Value
JRC	Joint Research Centre
LHV	Lower Heating Value
NEDC	New European Driving Cycle
NMHC	Non-Methane Hydro Carbons
NO_x	Nitrogen Oxides (NO & NO_2)
O_2	Oxygen
PFI	Port Fuel Injection
PI	Positive Ignition
PM	Particulate Matter
PN	Particle Number
TWC	Three Way Catalyst
UDC	Urban Driving Cycle (Part 1 of the NEDC driving cycle)

VELA	Vehicle Emission Laboratory

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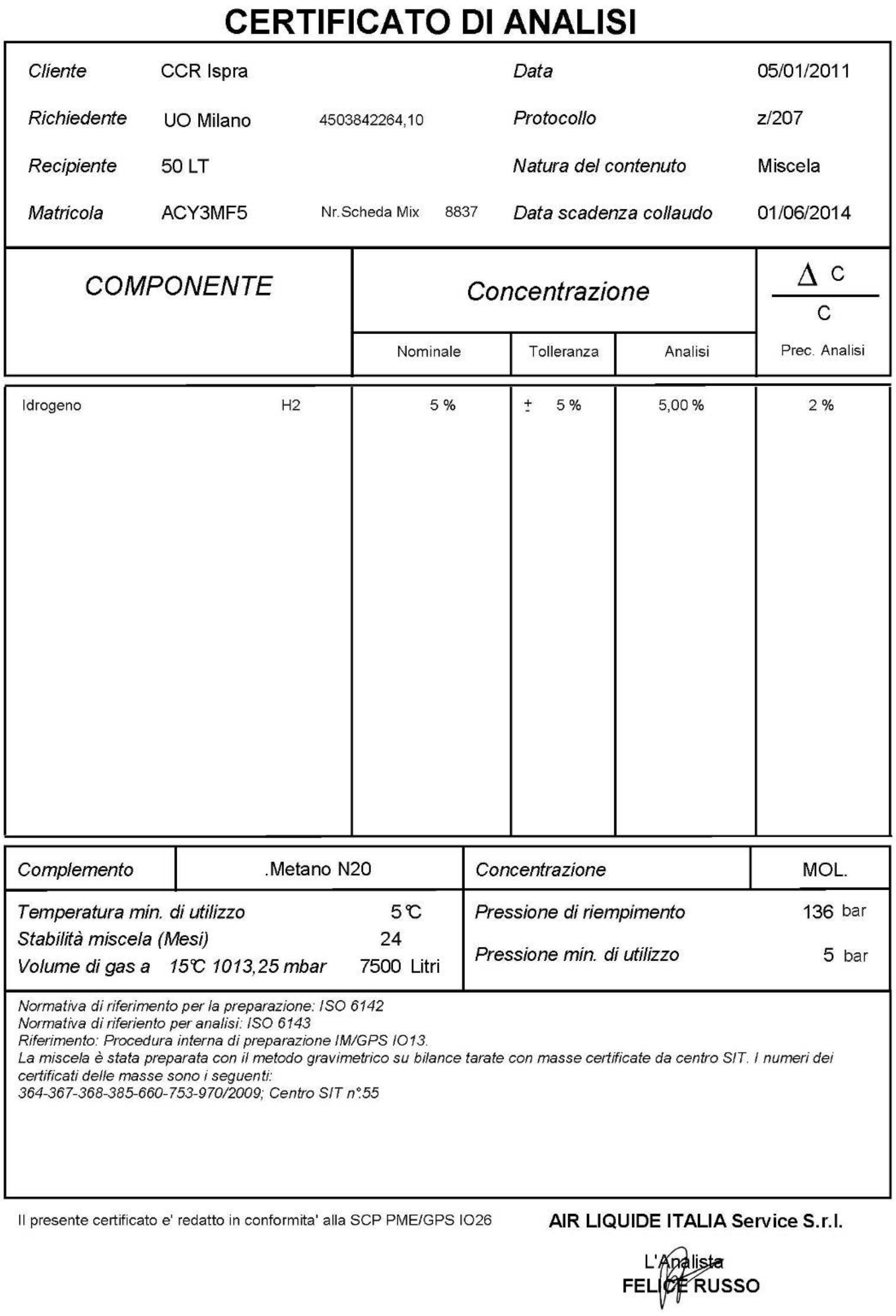
ANNEX I: CERTIFICATION OF ANALYSIS FOR H_2-CNG G20 BLENDS



CERTIFICATO DI ANALISI

Cliente	CCR Ispra		*Data*	05/01/2011
Richiedente	UO Milano	4503842264,10	*Protocollo*	z/207
Recipiente	50 LT		*Natura del contenuto*	Miscela
Matricola	ACY3MF5	Nr.Scheda Mix 8837	*Data scadenza collaudo*	01/06/2014

COMPONENTE		*Concentrazione*			$\frac{\Delta C}{C}$
		Nominale	Tolleranza	Analisi	Prec. Analisi
Idrogeno	H2	5 %	± 5 %	5,00 %	2 %

Complemento	.Metano N20	*Concentrazione*	MOL.
Temperatura min. di utilizzo	5℃	*Pressione di riempimento*	136 bar
Stabilità miscela (Mesi)	24		
Volume di gas a 15℃ 1013,25 mbar	7500 Litri	*Pressione min. di utilizzo*	5 bar

Normativa di riferimento per la preparazione: ISO 6142
Normativa di riferiento per analisi: ISO 6143
Riferimento: Procedura interna di preparazione IM/GPS IO13.
La miscela è stata preparata con il metodo gravimetrico su bilance tarate con masse certificate da centro SIT. I numeri dei certificati delle masse sono i seguenti:
364-367-368-385-660-753-970/2009; Centro SIT n°.55

Il presente certificato e' redatto in conformita' alla SCP PME/GPS IO26

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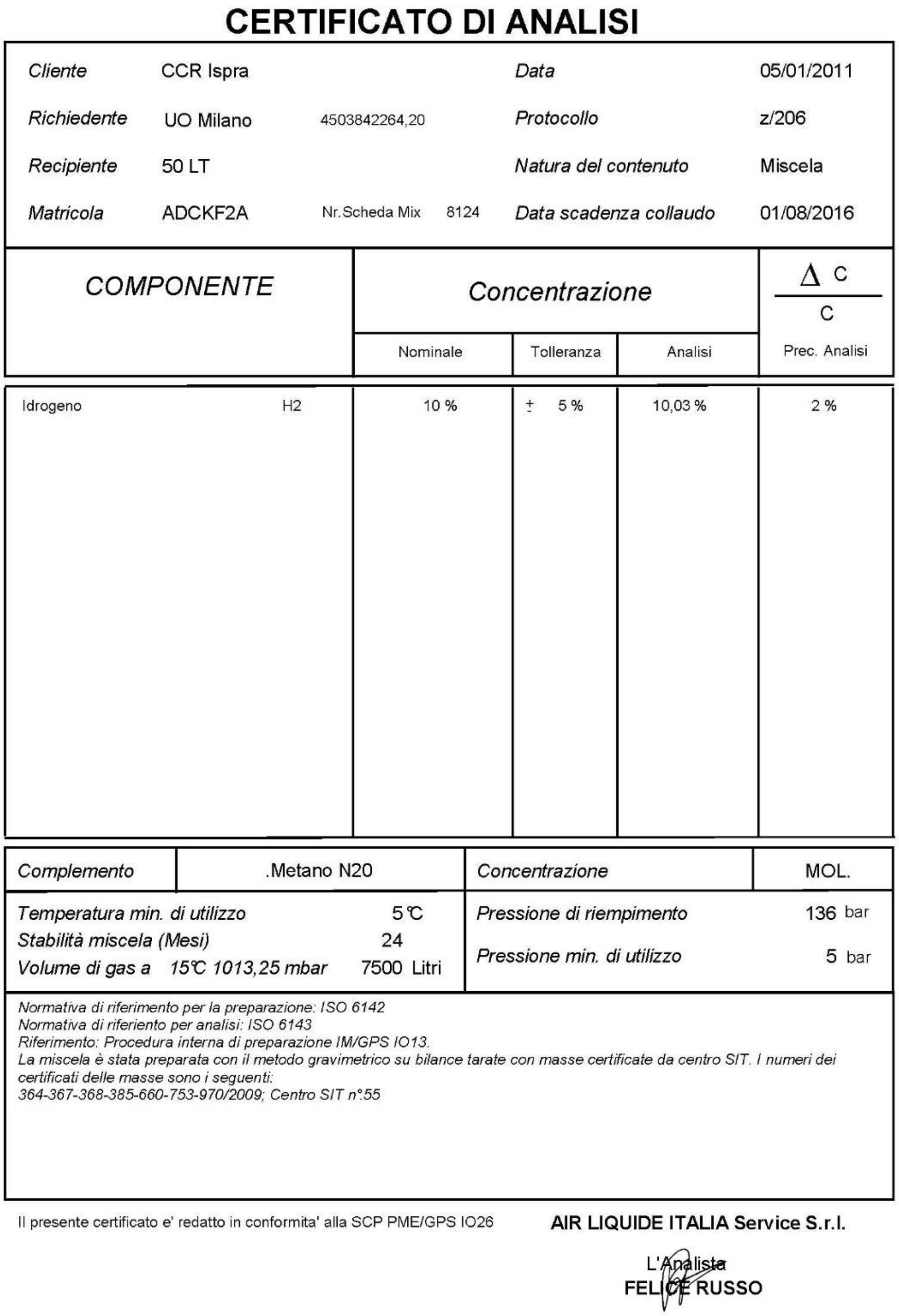

CERTIFICATO DI ANALISI

Cliente	CCR Ispra		*Data*	05/01/2011
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Recipiente	50 LT		*Natura del contenuto*	Miscela
Matricola	ADCKF2A	Nr.Scheda Mix 8124	*Data scadenza collaudo*	01/08/2016

COMPONENTE		*Concentrazione*			$\frac{\Delta C}{C}$
		Nominale	Tolleranza	Analisi	Prec. Analisi
Idrogeno	H_2	10 %	± 5 %	10,03 %	2 %

Complemento	.Metano N20	*Concentrazione*	MOL.

Temperatura min. di utilizzo	5℃	*Pressione di riempimento*	136 bar
Stabilità miscela (Mesi)	24	*Pressione min. di utilizzo*	5 bar
Volume di gas a 15℃ 1013,25 mbar	7500 Litri		

Normativa di riferimento per la preparazione: ISO 6142
Normativa di riferiento per analisi: ISO 6143
Riferimento: Procedura interna di preparazione IM/GPS IO13.
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CERTIFICATO DI ANALISI

Cliente	CCR Ispra		*Data*	05/01/2011
Richiedente	UO Milano	4503842264,30	*Protocollo*	z/201
Recipiente	50 LT		*Natura del contenuto*	Miscela
Matricola	AC92UD6	Nr.Scheda Mix 8123	*Data scadenza collaudo*	01/02/2015

COMPONENTE		*Concentrazione*			$\frac{\Delta C}{C}$
		Nominale	Tolleranza	Analisi	Prec. Analisi
Idrogeno	H2	15 %	± 5 %	15,03 %	2 %

Complemento	.Metano N20	*Concentrazione*	MOL.

Temperatura min. di utilizzo	5℃	*Pressione di riempimento*	136 bar
Stabilità miscela (Mesi)	24	*Pressione min. di utilizzo*	5 bar
Volume di gas a 15℃ 1013,25 mbar	7500 Litri		

Normativa di riferimento per la preparazione: ISO 6142
Normativa di riferiento per analisi: ISO 6143
Riferimento: Procedura interna di preparazione IM/GPS IO13.
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364-367-368-385-660-753-970/2009; Centro SIT n°55

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Cliente	CCR Ispra		*Data*	05/01/2011
Richiedente	UO Milano	4503842264,40	*Protocollo*	z/202
Recipiente	50 LT		*Natura del contenuto*	Miscela
Matricola	AD1M1FL	Nr.Scheda Mix 8838	*Data scadenza collaudo*	01/09/2015

COMPONENTE		*Concentrazione*			$\frac{\Delta C}{C}$
		Nominale	Tolleranza	Analisi	Prec. Analisi
Idrogeno	H_2	20 %	± 5 %	19,90 %	2 %

Complemento	.Metano N20	*Concentrazione*	MOL.

Temperatura min. di utilizzo	5℃	*Pressione di riempimento*	136 bar
Stabilità miscela (Mesi)	24	*Pressione min. di utilizzo*	5 bar
Volume di gas a 15℃ 1013,25 mbar	7500 Litri		

Normativa di riferimento per la preparazione: ISO 6142
Normativa di riferiento per analisi: ISO 6143
Riferimento: Procedura interna di preparazione IM/GPS IO13.
La miscela è stata preparata con il metodo gravimetrico su bilance tarate con masse certificate da centro SIT. I numeri dei certificati delle masse sono i seguenti:
364-367-368-385-660-753-970/2009; Centro SIT n°55

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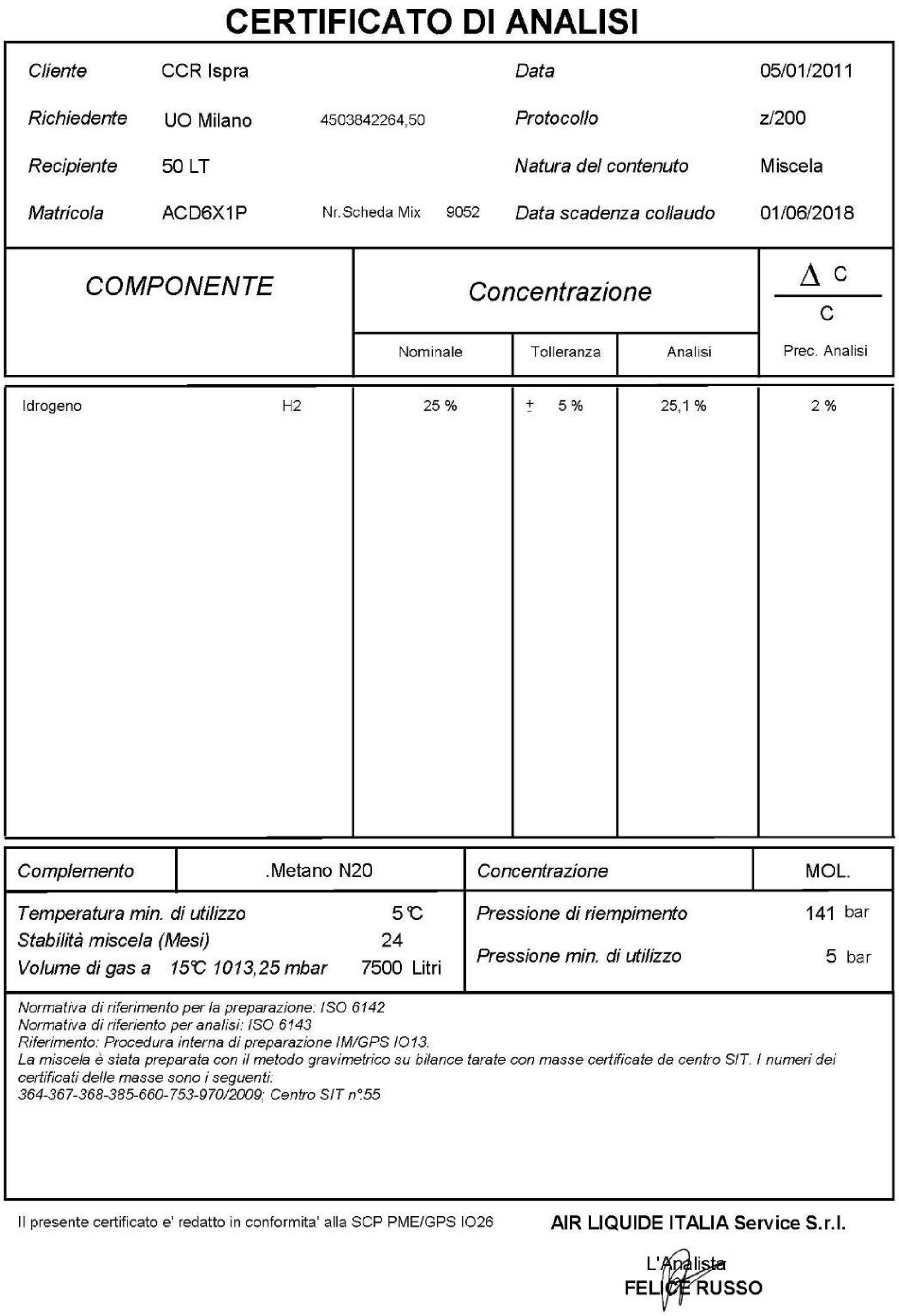

CERTIFICATO DI ANALISI

Cliente	CCR Ispra		*Data*	05/01/2011
Richiedente	UO Milano	4503842264,50	*Protocollo*	z/200
Recipiente	50 LT		*Natura del contenuto*	Miscela
Matricola	ACD6X1P	Nr.Scheda Mix 9052	*Data scadenza collaudo*	01/06/2018

COMPONENTE		*Concentrazione*			Δ C / C
		Nominale	Tolleranza	Analisi	Prec. Analisi
Idrogeno	H2	25 %	± 5 %	25,1 %	2 %

Complemento	.Metano N20	*Concentrazione*	MOL.

Temperatura min. di utilizzo	5℃	*Pressione di riempimento*	141 bar
Stabilità miscela (Mesi)	24	*Pressione min. di utilizzo*	5 bar
Volume di gas a 15℃ 1013,25 mbar	7500 Litri		

Normativa di riferimento per la preparazione: ISO 6142
Normativa di riferiento per analisi: ISO 6143
Riferimento: Procedura interna di preparazione IM/GPS IO13.
La miscela è stata preparata con il metodo gravimetrico su bilance tarate con masse certificate da centro SIT. I numeri dei certificati delle masse sono i seguenti:
364-367-368-385-660-753-970/2009; Centro SIT n°55

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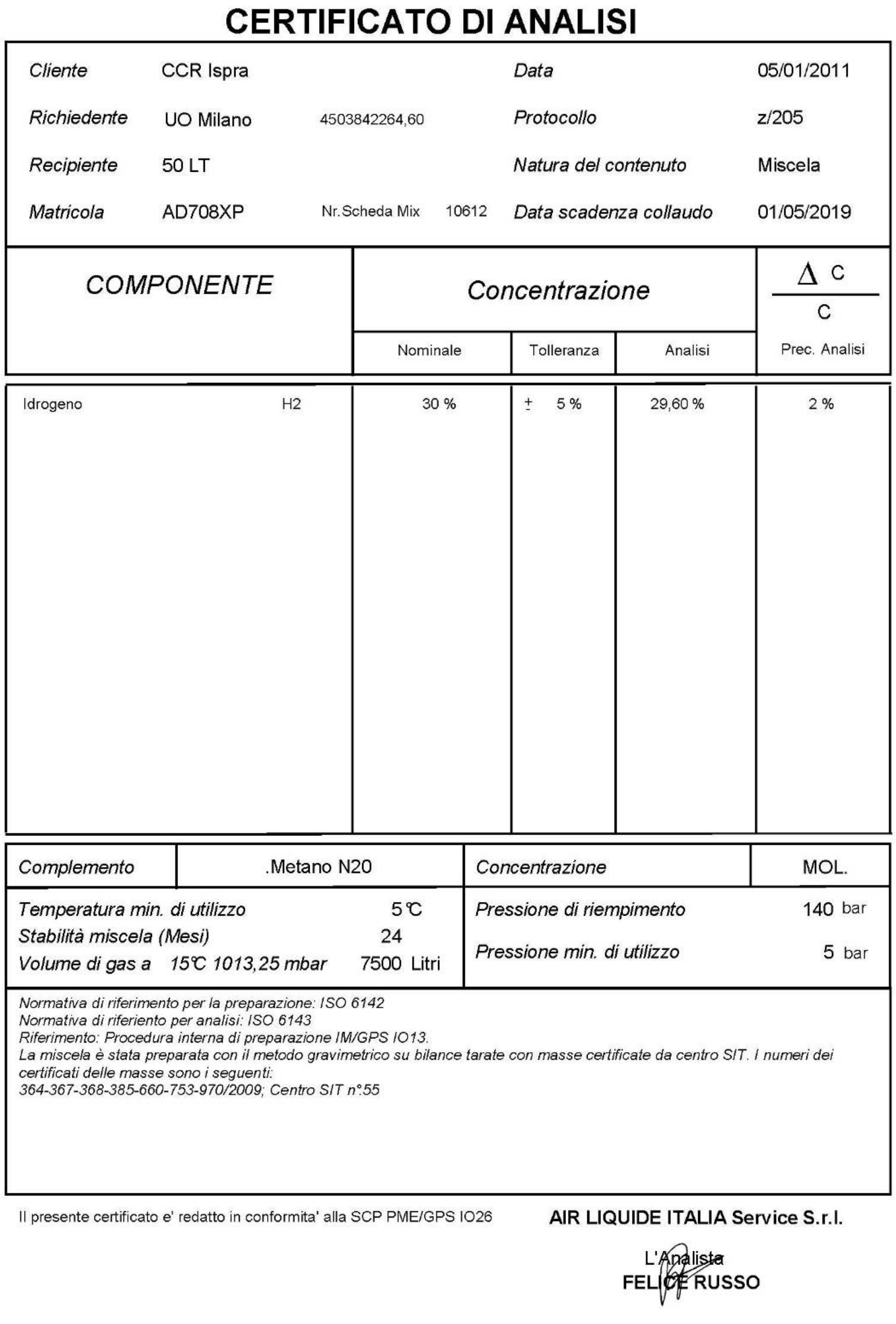

CERTIFICATO DI ANALISI

Cliente	CCR Ispra	*Data*	05/01/2011
Richiedente	UO Milano 4503842264,60	*Protocollo*	z/205
Recipiente	50 LT	*Natura del contenuto*	Miscela
Matricola	AD708XP Nr.Scheda Mix 10612	*Data scadenza collaudo*	01/05/2019

COMPONENTE		*Concentrazione*			$\frac{\Delta C}{C}$
		Nominale	Tolleranza	Analisi	Prec. Analisi
Idrogeno	H2	30 %	± 5 %	29,60 %	2 %

Complemento	.Metano N20	*Concentrazione*	MOL.
Temperatura min. di utilizzo	5℃	*Pressione di riempimento*	140 bar
Stabilità miscela (Mesi)	24	*Pressione min. di utilizzo*	5 bar
Volume di gas a 15℃ 1013,25 mbar	7500 Litri		

Normativa di riferimento per la preparazione: ISO 6142
Normativa di riferiento per analisi: ISO 6143
Riferimento: Procedura interna di preparazione IM/GPS IO13.
La miscela è stata preparata con il metodo gravimetrico su bilance tarate con masse certificate da centro SIT. I numeri dei certificati delle masse sono i seguenti:
364-367-368-385-660-753-970/2009; Centro SIT n°55

Il presente certificato e' redatto in conformita' alla SCP PME/GPS IO26

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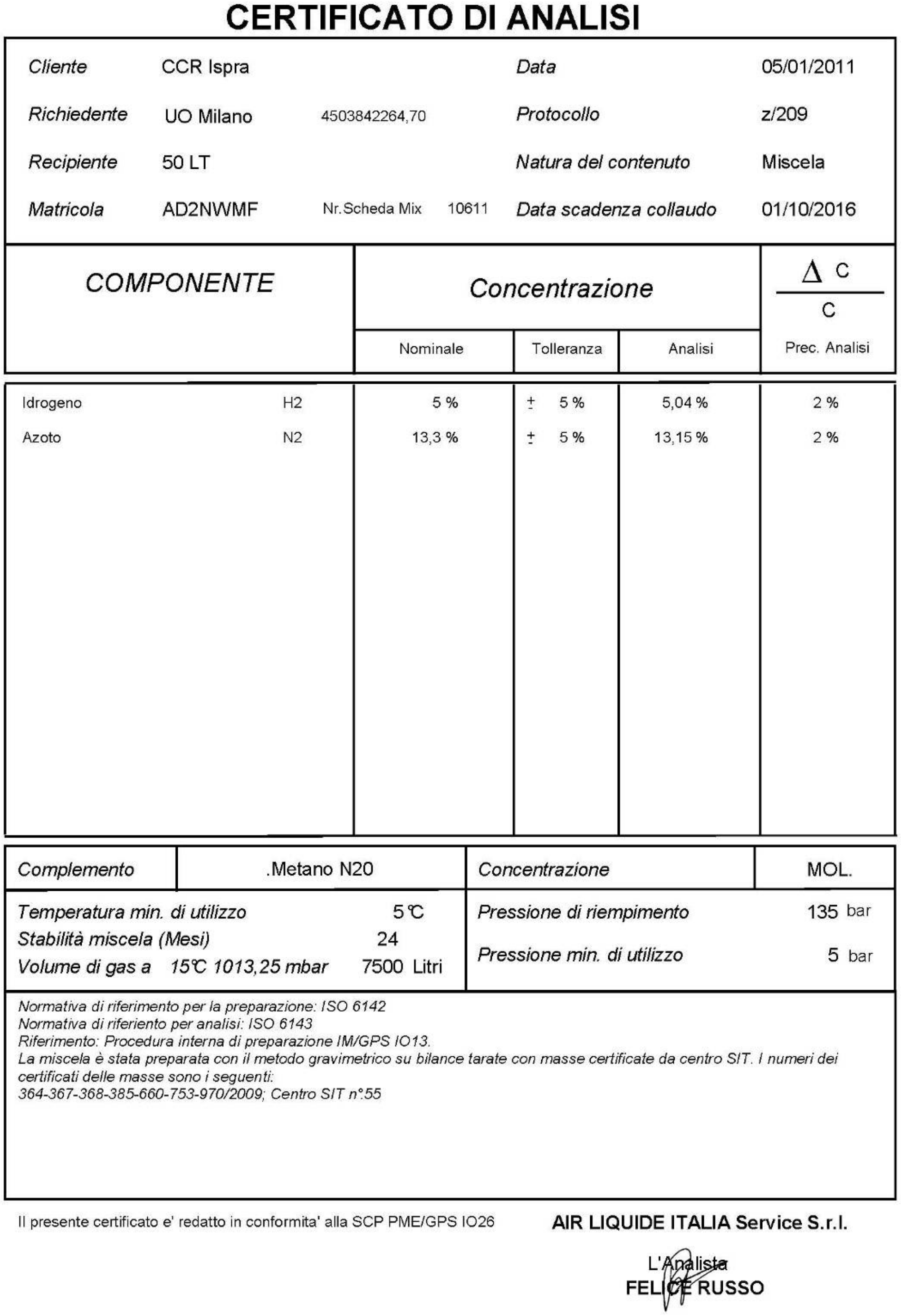
ANNEX II: CERTIFICATION OF ANALYSIS FOR H_2-CNG G25 BLENDS



CERTIFICATO DI ANALISI

Cliente	CCR Ispra		*Data*	05/01/2011
Richiedente	UO Milano	4503842264,70	*Protocollo*	z/209
Recipiente	50 LT		*Natura del contenuto*	Miscela
Matricola	AD2NWMF	Nr.Scheda Mix 10611	*Data scadenza collaudo*	01/10/2016

COMPONENTE		*Concentrazione*			$\frac{\Delta C}{C}$
		Nominale	Tolleranza	Analisi	Prec. Analisi
Idrogeno	H2	5 %	± 5 %	5,04 %	2 %
Azoto	N2	13,3 %	± 5 %	13,15 %	2 %

Complemento	.Metano N20	*Concentrazione*	MOL.
Temperatura min. di utilizzo	5℃	*Pressione di riempimento*	135 bar
Stabilità miscela (Mesi)	24	*Pressione min. di utilizzo*	5 bar
Volume di gas a 15℃ 1013,25 mbar	7500 Litri		

Normativa di riferimento per la preparazione: ISO 6142
Normativa di riferiento per analisi: ISO 6143
Riferimento: Procedura interna di preparazione IM/GPS IO13.
La miscela è stata preparata con il metodo gravimetrico su bilance tarate con masse certificate da centro SIT. I numeri dei certificati delle masse sono i seguenti:
364-367-368-385-660-753-970/2009; Centro SIT n°.55

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CERTIFICATO DI ANALISI

Cliente	CCR Ispra			*Data*	05/01/2011
Richiedente	UO Milano	4503842264,80		*Protocollo*	z/208
Recipiente	50 LT			*Natura del contenuto*	Miscela
Matricola	ACXC22G	Nr.Scheda Mix	10610	*Data scadenza collaudo*	01/07/2018

COMPONENTE		*Concentrazione*			$\frac{\Delta C}{C}$
		Nominale	Tolleranza	Analisi	Prec. Analisi
Idrogeno	H_2	10 %	± 5 %	10,06 %	2 %
Azoto	N_2	12,6 %	± 5 %	12,47 %	2 %

Complemento	.Metano N20	*Concentrazione*	MOL.

Temperatura min. di utilizzo	5℃	*Pressione di riempimento*	135 bar
Stabilità miscela (Mesi)	24	*Pressione min. di utilizzo*	5 bar
Volume di gas a 15℃ 1013,25 mbar	7500 Litri		

Normativa di riferimento per la preparazione: ISO 6142
Normativa di riferiento per analisi: ISO 6143
Riferimento: Procedura interna di preparazione IM/GPS IO13.
La miscela è stata preparata con il metodo gravimetrico su bilance tarate con masse certificate da centro SIT. I numeri dei certificati delle masse sono i seguenti:
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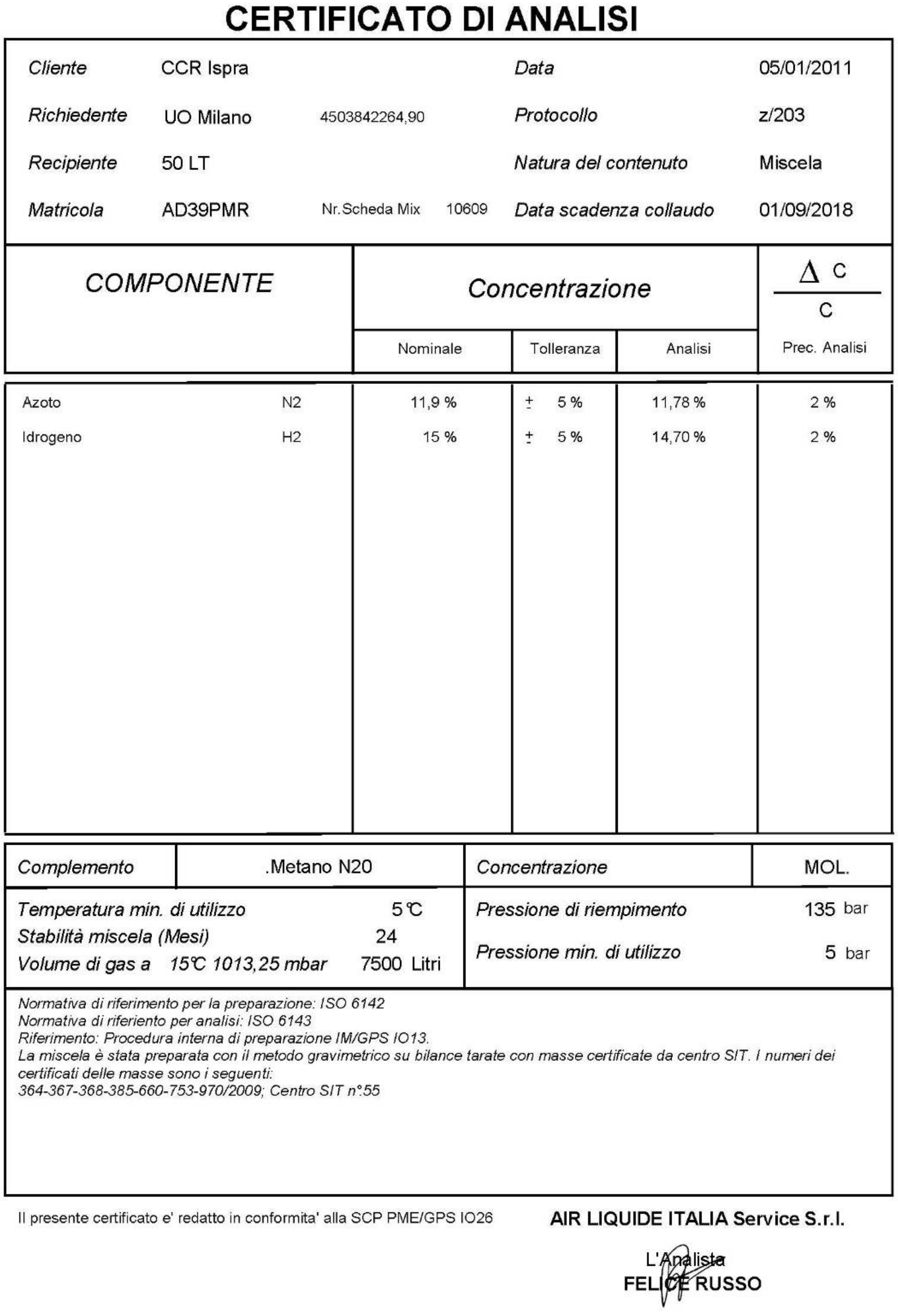

CERTIFICATO DI ANALISI

Cliente	CCR Ispra		*Data*	05/01/2011
Richiedente	UO Milano	4503842264,90	*Protocollo*	z/203
Recipiente	50 LT		*Natura del contenuto*	Miscela
Matricola	AD39PMR	Nr.Scheda Mix 10609	*Data scadenza collaudo*	01/09/2018

COMPONENTE		*Concentrazione*			$\frac{\Delta C}{C}$
		Nominale	Tolleranza	Analisi	Prec. Analisi
Azoto	N_2	11,9 %	± 5 %	11,78 %	2 %
Idrogeno	H_2	15 %	± 5 %	14,70 %	2 %

Complemento	.Metano N20	*Concentrazione*	MOL.

Temperatura min. di utilizzo	5 °C	*Pressione di riempimento*	135 bar
Stabilità miscela (Mesi)	24	*Pressione min. di utilizzo*	5 bar
Volume di gas a 15 °C 1013,25 mbar	7500 Litri		

Normativa di riferimento per la preparazione: ISO 6142
Normativa di riferiento per analisi: ISO 6143
Riferimento: Procedura interna di preparazione IM/GPS IO13.
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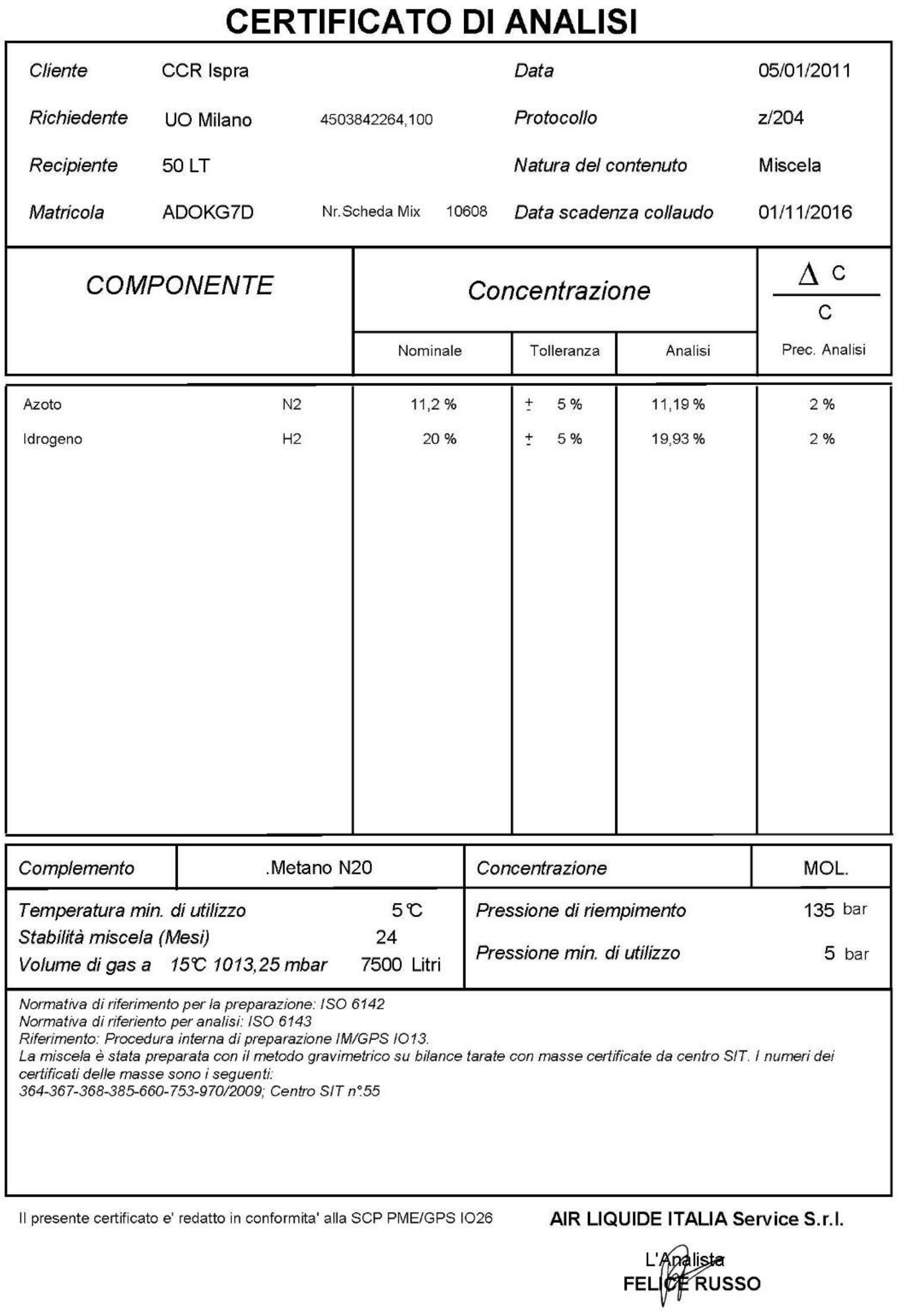
L'Analista
FELICE RUSSO



CERTIFICATO DI ANALISI

Cliente	CCR Ispra			*Data*	05/01/2011
Richiedente	UO Milano	4503842264,100		*Protocollo*	z/204
Recipiente	50 LT			*Natura del contenuto*	Miscela
Matricola	ADOKG7D	Nr.Scheda Mix	10608	*Data scadenza collaudo*	01/11/2016

COMPONENTE		*Concentrazione*			$\frac{\Delta C}{C}$
		Nominale	Tolleranza	Analisi	Prec. Analisi
Azoto	N2	11,2 %	± 5 %	11,19 %	2 %
Idrogeno	H2	20 %	± 5 %	19,93 %	2 %

Complemento	.Metano N20	*Concentrazione*	MOL.
Temperatura min. di utilizzo	5 °C	*Pressione di riempimento*	135 bar
Stabilità miscela (Mesi)	24	*Pressione min. di utilizzo*	5 bar
Volume di gas a 15°C 1013,25 mbar	7500 Litri		

Normativa di riferimento per la preparazione: ISO 6142
Normativa di riferiento per analisi: ISO 6143
Riferimento: Procedura interna di preparazione IM/GPS IO13.
La miscela è stata preparata con il metodo gravimetrico su bilance tarate con masse certificate da centro SIT. I numeri dei certificati delle masse sono i seguenti:
364-367-368-385-660-753-970/2009; Centro SIT n°55

Il presente certificato e' redatto in conformita' alla SCP PME/GPS IO26

AIR LIQUIDE ITALIA Service S.r.l.

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CERTIFICATO DI ANALISI

Cliente	CCR Ispra		*Data*	05/01/2011
Richiedente	UO Milano	4503842264,110	*Protocollo*	z/192
Recipiente	50 LT		*Natura del contenuto*	Miscela
Matricola	AD47FC3	Nr.Scheda Mix 10607	*Data scadenza collaudo*	01/06/2016

COMPONENTE		*Concentrazione*			$\frac{\Delta c}{c}$
		Nominale	Tolleranza	Analisi	Prec. Analisi
Azoto	N2	10,5 %	± 5 %	10,37 %	2 %
Idrogeno	H2	25 %	± 5 %	24,25 %	2 %

Complemento	.Metano N20	*Concentrazione*	MOL.
Temperatura min. di utilizzo	5℃	*Pressione di riempimento*	135 bar
Stabilità miscela (Mesi)	24	*Pressione min. di utilizzo*	5 bar
Volume di gas a 15℃ 1013,25 mbar	7500 Litri		

Normativa di riferimento per la preparazione: ISO 6142
Normativa di riferiento per analisi: ISO 6143
Riferimento: Procedura interna di preparazione IM/GPS IO13.
La miscela è stata preparata con il metodo gravimetrico su bilance tarate con masse certificate da centro SIT. I numeri dei certificati delle masse sono i seguenti:
364-367-368-385-660-753-970/2009; Centro SIT n°55

Il presente certificato e' redatto in conformita' alla SCP PME/GPS IO26

AIR LIQUIDE ITALIA Service S.r.l.

L'Analista
FELICE RUSSO

CERTIFICATO DI ANALISI

Cliente	CCR Ispra		*Data*	05/01/2011
Richiedente	UO Milano	4503842264,120	*Protocollo*	z/190
Recipiente	50 LT		*Natura del contenuto*	Miscela
Matricola	ACU6371	Nr.Scheda Mix 10606	*Data scadenza collaudo*	01/09/2016

COMPONENTE		*Concentrazione*			$\frac{\Delta C}{C}$
		Nominale	Tolleranza	Analisi	Prec. Analisi
Azoto	N_2	9,8 %	± 5 %	9,64 %	2 %
Idrogeno	H_2	30 %	± 5 %	30,17 %	2 %

Complemento	.Metano N20	*Concentrazione*	MOL.
Temperatura min. di utilizzo	5 °C	*Pressione di riempimento*	135 bar
Stabilità miscela (Mesi)	24	*Pressione min. di utilizzo*	5 bar
Volume di gas a 15°C 1013,25 mbar	7500 Litri		

Normativa di riferimento per la preparazione: ISO 6142
Normativa di riferiento per analisi: ISO 6143
Riferimento: Procedura interna di preparazione IM/GPS IO13.
La miscela è stata preparata con il metodo gravimetrico su bilance tarate con masse certificate da centro SIT. I numeri dei certificati delle masse sono i seguenti:
364-367-368-385-660-753-970/2009; Centro SIT n°55

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ANNEX III: CALCULATION FORMULAS FOR REVIEWING REGULATION 692/2008

For obvious reasons the calculations of the fuel consumption for the different mixtures (blends) with hydrogen needs to be adapted from the regulatory ones in order to take into consideration the inclusion of hydrogen in the fuel blend. The fuel consumption, expressed in m^3 per 100 km (in the case of NG and H2NG) is given by the following expression:

$$FC = \frac{910{,}4 \cdot A + 13.600}{44{,}655 \cdot A^2 + 667{,}08 \cdot A}\left(\frac{7{,}848 \cdot A}{9{,}104 \cdot A + 136} \cdot HC + 0{,}429 \cdot CO + 0{,}273 \cdot CO_2\right)$$

Where:

HC = the measured emission of hydrocarbons in g/km

CO = the measured emission of carbon monoxide in g/km

CO_2 = the measured emission of carbon dioxide in g/km

A = quantity of CNG within the H_2-CNG mixture, expressed in per cent volume

Furthermore the following needs to be taken into considertion:

The dilution factor is calculated as follows:

For each reference fuel, except hydrogen

$$DF = \frac{X}{C_{CO2} + \left(C_{HC} + C_{CO}\right) \cdot 10^{-4}}$$

For a fuel of composition $C_xH_yO_z$, the general formula is:

$$X = 100 \frac{x}{x + \frac{y}{2} + 3{,}76 \cdot \left(x + \frac{y}{4} - \frac{z}{2}\right)}$$

In particular for H_2-CNG, the formula is:

$$X = \frac{65{,}4 \cdot A}{4{,}922A + 195{,}84}$$

For hydrogen, the dilution factor is calculated as follows:

$$DF = \frac{X}{C_{H2O} - C_{H2O-DA} + C_{H2} \cdot 10^{-4}}$$

European Commission
EUR 25899 – Joint Research Centre – Institute for Energy and Transport

Title: Evaluation of a Euro 4 vehicle with various blends of CNG/H_2 fuel

Author(s): Adolfo Perujo, Christos Dardiotis, Urbano Manfredi

Luxembourg: Publications Office of the European Union

2013 – 58 pp. – 21.0 x 29.7 cm

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Abstract
The report presents the main results of an experimental campaign carried out by the JRC in the support of the legislative activities on type approval of hydrogen-powered motor vehicles. It serves as the scientific and technical basis to test the proposed methods for type approval regarding vehicles using a variable mixture of H_2 and Compressed Natural Gas (CNG).
A prototype bi-fuel vehicle is tested, designed to operate either on petrol or on various H_2-CNG blends, with maximum percentage of 30% H_2 on CNG. The methodology used to estimate the unburned hydrocarbon's density, the fuel density, the fuel consumption, and the heating value of each H_2-CNG blend in presented. The bag and modal gaseous emissions, as well as the particulate emission performances of the vehicle tested under the various H_2-CNG blends and on petrol fuel is presented. It can be concluded that the use of such fuel mixtures can provide a positive input to the reduction of pollutant emissions as well as of greenhouse gas emissions.

LD-NA-25899-EN-N

As the Commission's in-house science service, the Joint Research Centre's mission is to provide EU policies with independent, evidence-based scientific and technical support throughout the whole policy cycle.

Working in close cooperation with policy Directorates-General, the JRC addresses key societal challenges while stimulating innovation through developing new standards, methods and tools, and sharing and transferring its know-how to the Member States and international community.

Key policy areas include: environment and climate change; energy and transport; agriculture and food security; health and consumer protection; information society and digital agenda; safety and security including nuclear; all supported through a cross-cutting and multi-disciplinary approach.

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