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Emissions of modern light duty ethanol flex-fuel vehicles over different operating and environmental conditions ☆

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HIGHLIGHTS

- Various ethanol blends tested in 2 Flex Fuel Vehicles of different fueling system.
- Tests performed at 22 °C and −7 °C, under certification and more transient cycles.
- At 22 °C CO emissions decreased using E85, HC emissions were practically unaffected.
- NO_x emissions presented different behavior over NEDC and CADC for the 2 vehicles.
- At −7 °C both regulated CO and total HC emissions increased with the use of E75.

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ABSTRACT

In 2012 some 2.8 million toe of bioethanol were introduced in the European gasoline market. The introduction of ethanol blendstocks in the European fuels market should take place without undermining pollutant emissions or vehicle engine performance. According to the Euro 5 certification procedure the properties of three different ethanol blends supplied in the European market (E5, E75, E85) should be taken into account when testing for exhaust emissions. In this study the latest procedure established for emissions certification is assessed, shedding light on the gaseous regulated emissions and CO_2 – energy/fuel consumption performance of two Flex Fuel Vehicles with different fueling strategies (Direct/Port Fuel Injection) and different Euro standards (Euro 4 and Euro 5). Both legislative and non-legislative "real-world" driving cycles were used in the study. The analysis is completed with a comparison with existing emission factors for Flex Fuel Vehicles in Europe. At 22 °C CO emissions decreased over all conditions tested with the use of the high ethanol content fuel (E85), compared to the E5 performance. Total HC emissions were practically unaffected by the fuel type. NO_x emissions decreased for both vehicles over the New European Driving Cycle, while over the Common Artemis Driving Cycle the vehicles exhibited different NO_x behavior. At −7 °C both regulated CO and total HC emissions increased with E75 fuel. However, the Euro 5 vehicle exhibited emission performance below the current legislative limits for both CO/total HC over the cold-start urban part of the cycle. Results were found to be in line with existing emission factors used in Europe for ethanol-fueled vehicles.

Abbreviations: CADC, Common Artemis Driving Cycle; COPERT, computer programme to calculate emissions from road transport; CVS, Constant Volume Sampling; EC, Energy Consumption; ECU, Engine Control Unit; EU, European Union; EMEP/EEA, European Monitoring and Evaluation Programme/European Environmental Agency; EUDC, Extra Urban Driving Cycle; Euro #, emission standard; FC, Fuel Consumption; FFV, Flex Fuel Vehicle; FID, Flame Ionization Detector; G-DI, Gasoline Direct Injection; GHG, Greenhouse Gas; JRC, Joint Research Centre; NEDC, New European Driving Cycle; NMHC, Non Methane Hydrocarbons; PFI, Port Fuel Injection; TWC, Three Way Catalyst; UDC, Urban Driving Cycle; VELA, Vehicle Emission Laboratory.

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1. Introduction

The use of biofuels in Europe has been promoted for the past ten years in an effort to reduce road transport generated Greenhouse Gas (GHG) emissions and strengthen energy security. So far one of the most popular biofuel has been biodiesel but biomass derived ethanol has also gained an important market share in various European countries, reaching a total European Union (EU) wide production of 2.8 million toe in 2010 [1]. Ethanol has been proposed as a potential fuel for gasoline engines since the early 20th century, due to some favorable characteristics such as its high octane number. With respect to GHG savings, stoichiometric combustion of Ethanol delivers more energy for each kilogram of Carbon Dioxide (CO_2) produced (14.1 instead of ~13.5 MJ/kg CO_2) [2]. However the availability of fossil gasoline at a relatively low price, until recently, has limited the use of ethanol as an automotive fuel. Meanwhile, concerns about urban air quality and the adverse health effects associated with road transport generated emissions, have led to the adoption of increasingly more stringent pollutant emission limits during the past 30 years, which have driven the evolution of exhaust after-treatment systems and internal combustion engine technologies to high levels of efficiency and optimization. The recent introduction of ethanol blendstocks in the fuels market should take place without undermining pollutant emissions or vehicle engine performance.

The "Cold-start Carbon Monoxide (CO) and total Hydrocarbons (HC) performance for gasoline vehicles, at low ambient temperature conditions", conducted at −7 °C (Type VI test) is one of the legislative emission type-approval tests for new light duty vehicles in the EU. The test is run over the urban part of the New European Driving Cycle (NEDC) and is applicable only to spark ignition vehicles. The current emission limits for this test are 15 and 1.8 g/km for CO and total HC respectively, carried over since the introduction of Euro 3/4 requirements [3], in 2000. The European Commission has been requested to update these limits [4], in order to be consistent with the Euro 5/6 Type I test (measured at an ambient temperature from 20 to 30 °C). Meanwhile, the current emission limits and Type VI test requirements have been extended also for Euro 5 Flex Fuel Vehicles (FFV) [5] while operating on both fuels (E5 and E75), since up to Euro 3/4 only the mono-fuel gasoline vehicles where applicable to such a certification test. This paper discusses the performance of two FFVs tested also over the Type VI test for Ethanol Flex Fuel Vehicles.

In the literature some studies have already investigated the performance of Euro 3/4 FFVs under low temperature conditions (−7 °C) [6–8], but all the emissions and fuel consumption have been calculated according to the Euro 4 procedure [3]. This affects the results, as it will be discussed in detailed in this paper, since according to the Euro 5 certification procedure [5,9], the different ethanol blend (E5, E75, E85) properties are taken into consideration, in terms of unburned hydrocarbon density, fuel density, and fuel consumption carbon balance formula. In this study the latest procedure is followed, shedding light on the gaseous regulated emissions and CO_2 – energy/fuel consumption performance of the two vehicles tested, of different emission certification (Euro 4/5) and different injection strategy (Port Fuel/Direct Injection), under legislative and non-legislative "real-world" driving cycles. The analysis is completed with a comparison with existing emission factors for FFVs in Europe.

2. Experimental

2.1. Vehicles and fuels

Two gasoline FFVs were investigated in this study: The first vehicle (henceforward V1) was a late technology Euro 5 compliant Gasoline Direct Injection (G-DI) and turbocharged, while the second (V2) was a Euro 4 Port Fuel Injection (PFI) vehicle. Table 1 provides the main characteristics of these vehicles

Both vehicles were equipped with a Three Way Catalyst (TWC) for the control of regulated gaseous pollutants, CO, HC and Nitrogen Oxides (NO_x). By the time when the experimental campaign was taking place (1st quarter of 2011), only one Euro 5 FFV was available in the market. Thus, it was decided that a 2nd vehicle to be included in the campaign, a Euro 4 compliant one (V2).

V1 had mileage below 3000 km at the beginning of the experimental campaign. UNECE Regulation 83 [9] requires that for type approval purpose the vehicles must have been driven at least 3000 km prior to emission testing. In the current testing campaign, due to the limited number of repetitions the limited mileage was expected to have a reduced influence in respect to the objective of the study.

Three fuels differing for the ethanol content were used in this study. The reference fuel (henceforward E5) was a blend of gasoline and 5% v/v ethanol, the second fuel (E75 from now on) had an ethanol content of 75% v/v and the third fuel (E85) an ethanol content of 85% v/v. E5 and E85 were used and evaluated over tests performed at 22 °C, while at low ambient temperature conditions (−7 °C) the E5 and the E75 were used. In Europe, during winter time, E85 fuel for FFV vehicles is replaced by a lower ethanol content blend (E75) in order to avoid problems associated with engine starting. The specifications of E75 reference fuel are defined in Commission Regulation No. 566/2011 [5]. Table 2 presents the main specifications of the fuels used in this study.

The fuel drain/re-filling was done according to the respective procedure described in [10]. After this procedure the vehicle was preconditioned running one UDC and two EUDC part cycles on the vehicle dynamometer. Additionally, for V1, the adaptation of the engine's fuel injection system on the new fuel was verified reading the "Alcohol percentage in fuel" of the Engine Control Unit (ECU) recording at the end of the preconditioning driving protocol.

2.2. Driving cycles and measurement protocol

The vehicles were tested over the New European Driving Cycle (NEDC) and the Common Artemis Driving Cycle (CADC) at two temperatures (22 °C & −7 °C). The NEDC is the cycle employed in EU since 2000 for certification of light-duty vehicles. It consists of the urban part, commonly indicated as Urban Driving Cycle (UDC), which includes four repetitions of the Elementary Urban Cycle, and the Extra-Urban Driving Cycle (EUDC) [9]. The CADC is a hot start cycle developed in the framework of the EU funded Artemis project [11]. It consists of three segments representative of typical urban, rural and motorway driving conditions in Europe (with an average speed of 17.5 km/h, 60.3 km/h and 116.4 km/h, respectively).

For V1 the daily test sequence consisted of one cold start NEDC (at least 12 h soak time), and one hot start CADC, conducted as soon as possible after the NEDC (~30 min).

The daily test sequence of V2 was different: Each testing day consisted of one cold start NEDC and one cold-start CADC (6 h soak

Table 1
Flex fuel gasoline vehicles' data and specifications.

Vehicle	Emission standard	Injection system	Engine capacity/rated power	Mileage (km)	CO_2 emission (type approval) (g/km)
V1	Euro 5	G-DI	1984 cc/132 kW	1411	154
V2	Euro 4	PFI	1798 cc/92 kW	11,772	177

Table 2
Fuels' main specifications.

Property	E5	E75	E85	Method
Chemical formula	$C_1H_{1.89}O_{0.016}$	$C_1H_{2.61}O_{0.329}$	$C_1H_{2.74}O_{0.385}$	[5]
Research octane no.	95.1	102	107.8	EN ISO 5164
Motor octane no.	86.4	88	89.0	EN ISO 5163
Ethanol content (% vol)	5.0	73.7	85.7	EN 13132
Density (15 °C) (kg/m^3)	744.3	772.8	785.7	EN ISO 12185
Dry vapor pressure equivalent (kPa)	67.2	50.3	35.16	EN 13016-1
Lower heating value (MJ/kg)	41.98	30.85	29.43	ASTM D3338
Lower heating value per volume (MJ/l)[a]	31.25	23.84	23.12	
Carbon weight fraction (%)	84.751	60.339	57.379	ASTM D3343
Hydrogen weight fraction (%)	13.442	13.216	13.194	ASTM D3343
Oxygen weight fraction (%)	1.806	26.444	29.427	EN 13132
Stoichiometric air to fuel ratio[a]	14.21	10.28	9.80	
CO_2 emissions (kg/kg fuel)[a]	3.11	2.21	2.11	
Energy per CO_2 emitted (MJ/kg CO_2 emitted)[a]	13.50	13.93	13.98	

[a] Calculated values: see Supplementary material, S2: Fuel properties calculations.

Table 3
Number of test repetitions performed for each combination of vehicle, test cell temperature, fuel and driving cycle (NEDC: New European Driving Cycle, CADC: Common Artemis Driving Cycle).

Vehicle		V1				V2			
Temperature (°C)		22		−7		22		−7	
Fuel		E5	E85	E5	E75	E5	E85	E5	E75
NEDC	UDC (cold start)	5	3	3	3	4	3	4	3
	EUDC (hot start)	5	3	3	3	4	3	4	3
CADC	URBAN (hot start)	4	3	2	2	–	–	–	–
	RURAL (hot start)	4	3	2	2	2	2	2	2
	MOTORWAY (hot start)	4	3	2	2	2	2	2	2

time). For this reason, the CADC Urban part of the V2 is excluded from the following analysis. Table 3 summarizes the number of the test repetitions conducted for each combination of vehicle/cycle/temperature/fuel/cycle part.

2.3. Instruments – legislation requirements

The measurements were conducted at the Vehicle Emission Laboratory (VELA) test cell of the Joint Research Centre (JRC). The test cell was equipped with a chassis dynamometer[1] and a Constant Volume Sampling (CVS) system.[2] The measurements and the gaseous emissions/fuel consumption calculations of both vehicles were performed according to the current legislative procedures for type approval of Euro 5/6 light duty vehicles [5,9,12]. However, the low temperature test, performed at −7 °C, was not required for Euro 4 certified V2, when running on high ethanol content blend, therefore no procedure was defined in the relevant legislation [3,13]. Moreover, V2 (Euro 4) was not required to be tested for emissions when running on E85, neither at regular (20–30 °C), nor at low ambient temperature (−7 °C). It was decided to use exactly the same procedure as required for Euro 5 FFVs [5,9,12]. In addition to the regulated pollutants at low temperature for gasoline vehicles (CO and total HC), NO_x emissions were also measured for both vehicles, as well as CO_2 emissions. The bag gaseous emissions were available for the NEDC as well as for both UDC and EUDC parts. For the CADC the bag gaseous emissions were available for each part (urban, rural, motorway).

An analyzer bench was employed for bag gaseous emission measurement (NO_x, total HC, Methane (CH_4),[3] CO and CO_2). In addition, second by second modal data analysis of the raw undiluted exhaust gas was performed with monitoring rate of 1 Hz.

The dynamometer loads prescribed by the legislation were used (Type I test, 22 °C) since the actual vehicles' road coast down data were not available. For the low temperature test (−7 °C) the dynamometer loads were increased to produce a decrease of coast down times by 10% for both vehicles tested, as required by the legislation for gasoline vehicles, since no coast down data measured at −7 °C was available.

For V1 an ECU data logging instrument was used to monitor various engine operating characteristics during testing, such as temperatures, pressures, engine/vehicle speed, intake air mass flow rate, ignition timing, accelerator pedal position, alcohol percentage in fuel.

It is worth to mention that according to Euro 5 emission standard requirements (applied in this study), the HC density used for the calculation of respective mass emissions for E85 is 0.932 g/l, instead of 0.631 g/l for E5. This leads to ~50% elevated HC mass emissions of E85, compared to E5, for the same concentration in the bag. Moreover, the European legislation uses the same procedure for measuring the HC vehicle emissions (Flame Ionization Detector – FID), irrespective of the fuel's ethanol content (E5 or E85). However, the by-products of the ethanol's incomplete combustion (alcohol, aldehydes) are by definition not hydrocarbons, since they also contain oxygen. In the United States [14] the alcohol emissions are measured separately and the FID measurement is corrected for the presence of oxygenated HCs (taking into account the ethanol's response factor). The correction of the HC emission measurement of ethanol content fuels is out of the scope of this study. More details can be found elsewhere [15–17].

3. Results and discussion

3.1. Gaseous pollutants

3.1.1. NEDC results

Fig. 1 shows the gaseous emission bag results (CO, total HC and NO_x) over the NEDC (Fig. 1a), UDC (Fig. 1b) and EUDC (Fig. 1c) at

[1] A four Wheel-Drive (4WD) chassis dynamometer was used. However, for the scope of this study the 2WD configuration was employed. The roller bench of the chassis dynamometer was a single roller type with roller diameter: 48 in, maximum traction force: 3300 Nm, inertia range: 454–2720 kg.

[2] The CVS flow rate was 9 and 6 m^3/min for V1 and V2 respectively.

[3] The CH_4 emissions were measured for both vehicles, since apart from the total HC, the Non-Methane Hydrocarbon (NMHC) emissions are also included among the regulated gaseous pollutants of Type I test (Euro 5/6 emission standards).

22 °C for all vehicle/fuel combinations. The same scale is used for all the cycle parts for a direct comparison. The relevant emission limits for Type I test (22 °C over the NEDC) are also shown for each pollutant. The average gaseous emission values and the standard deviation of the average values over the NEDC, UDC and EUDC at both test temperatures for both vehicles tested can be found in the Supplementary Material (Table S1). Both vehicles comply with the limits; however, a comparison of the measured values with the respective type-approval ones is out of the scope of this study. Moreover, for both vehicles the calculation of the gaseous pollutants was done according to the Euro 5 provisions. A direct comparison of the two vehicles is also out of the scope of this study. Although the vehicles represent different engine technologies and emission standards, the limited number of vehicles tested (one of each Euro 4/5 emission standard category) does not allow to generalize their results to all Euro 4/5 FFVs.

The variability of the results, denoted by the standard deviation error bars, indicates that higher variability is show at the NEDC results, compared to the respective CADC (Fig. 5). The reason for this could be attributed to the fact that the NEDC is a cold start cycle, where several factors affect the repeatability of a measurement (vehicle pre-conditioning, soak time, etc.), despite the fact that the legislation requirements were strictly followed during the specific campaign. Moreover, more NEDC test repetitions were run for this campaign, compared to CADC test repetitions (only two in most cases).

Both vehicles showed decreased CO emissions when tested with the E85, compared to the respective results with the E5. A possible explanation could be attributed to the lower engine-out CO emissions when operating with elevated ethanol content fuel, due to the elevated oxygen content of the E85 fuel [18,19]. The oxygen contained in the fuel improves the combustion process by locally modifying the air/fuel ratio. The fuel's incomplete combustion is reduced, reducing also the CO and HC formation. However, the results vary from study to study; in some cases CO emissions decreased using E85, while in other studies the outcome was on the opposite direction [7]. In some studies both behaviors were reported for different vehicles, concerning both CO and total HC emissions [6,8].

An additional factor that influences emissions over the NEDC is the cold-start and light-off performance of the TWC, over the UDC. The results shown in this study are referred to tailpipe emissions, consequently, it is difficult to distinguish whether the decreased CO emissions reported were due to the lower engine-out emission or to improved TWC performance when high ethanol blend fuel was used. However, in the case of the direct injection V1 the warming-up of the TWC can be controlled effectively, regardless of the fuel used, as show in Fig. 2b: The evolution of the exhaust catalyst temperature that reaches for both fuels ~600 °C within the first ~70 s of the cycle – derived by the ECU recording – and the simultaneous reduction of the CO concentration (Fig. 2a), regardless of the operating fuel, imply a similar warming-up and light-off performance of the TWC for both tests. During the cold-start period the tailpipe emissions are dominated by the engine combustion characteristics, described in the previous paragraph. Consequently, for V1 the lower emissions over the cold-start period with E85 (Fig. 2a) can be attributed to the improved combustion characteristics and not to the similar for both fuels TWC performance.

The total HC emissions were not affected by the fuel used for both vehicles, giving comparable HC mass emissions for E5 and E85 for the vehicles tested (Fig. 1, HC). However, a closer insight on the V1 instantaneous tailpipe HC emissions reveals different behavior of HC concentration, during cold-start (Fig. 3, first 100 s of UDC are shown). Fig. 3a shows the evolution of the HC concentration: the peak concentration for E5 resulted in more than 4000 ppm, while E85 reached lower levels (~2500 ppm), behavior similar to the CO concentration (Fig. 2a). However, the evolution of the HC instantaneous mass flow rate (Fig. 3b), as calculated from the (similar for both fuels) exhaust flow rate (also shown in Fig. 3b), was similar for both fuels, resulted in a peak mass of ~0.04 g for both fuels. Thus, the higher E85 HC mass is solely attributed to the higher (by ~50% compared to E5, according to

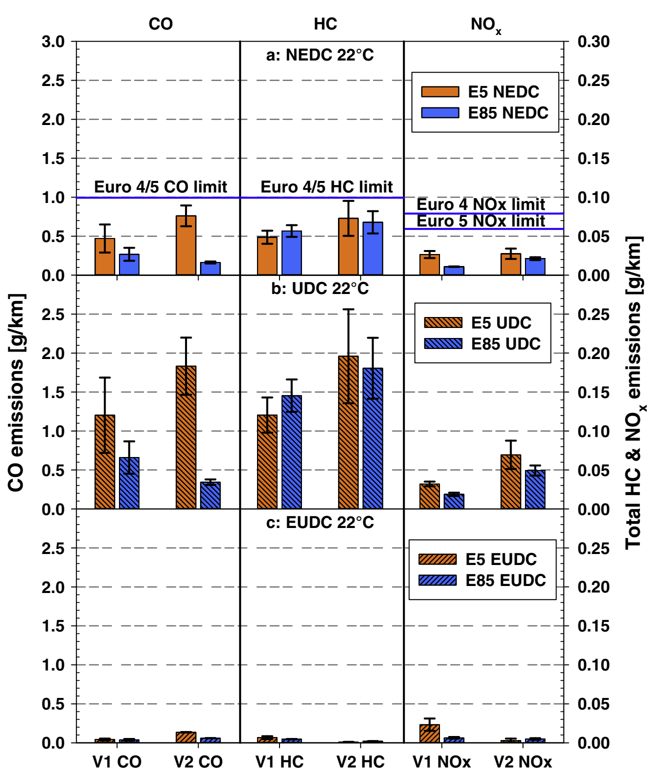

Fig. 1. Carbon monoxide (CO), total Hydrocarbon (HC) and Nitrogen Oxides (NO_x) average bag emissions over the (a) New European Driving Cycle (NEDC), (b) Urban Driving Cycle (UDC) and (c) Extra Urban Driving Cycle (EUDC) at 22 °C for the vehicles tested with E5 and E85 fuels. Error bars: standard deviation of average measured values.

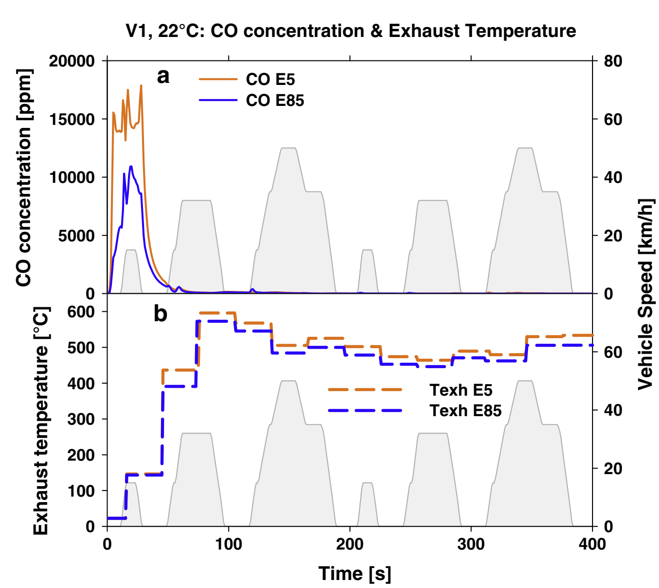

Fig. 2. (a) Instantaneous CO tailpipe concentration and (b) exhaust temperature (before the TWC) derived by the Engine Control Unit recordings over the first half of the Urban Driving Cycle (UDC) for fuels E5 and E85 at 22 °C for V1.

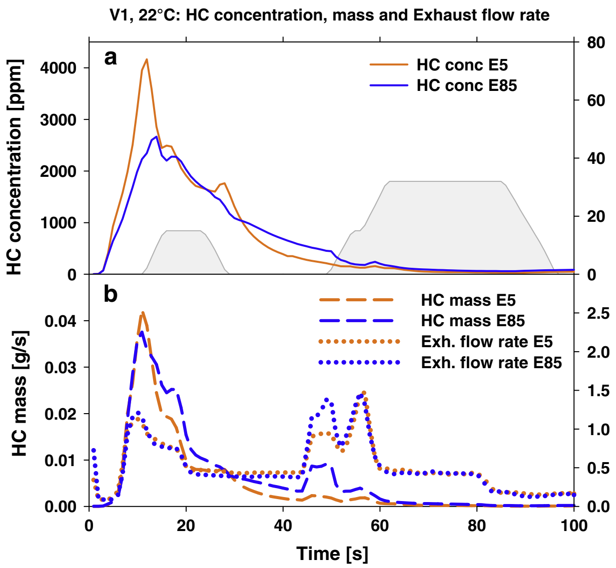

Fig. 3. (a) Instantaneous tailpipe HC concentration and (b) instantaneous tailpipe HC mass flow rate and engine exhaust flow rate over the first 100 s of the Urban Driving Cycle (UDC) for fuels E5 and E85 at 22 °C for V1.

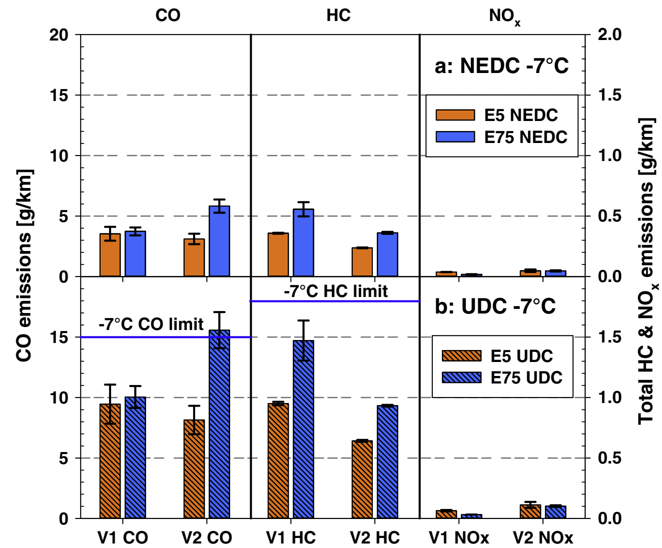

Fig. 4. CO, total HC and NO_x average bag emission values over (a) the New European Driving Cycle (NEDC) and (b) the Urban Driving Cycle (UDC) at −7 °C for the vehicles tested with E5 and E75 fuels. Error bars: standard deviation of average measured values.

Euro 5 requirements) HC density, used for HC mass emission calculation.

Fig. 1a shows the average NO_x emissions of both FFVs tested, at 22 °C over the NEDC. In general, NO_x engine-out emissions are affected by the operational characteristics of the engine such as the air/fuel ratio, the burned gas fraction in the in-cylinder unburned mixture (residual plus recycled exhaust gas), and the ignition timing [20]. If the combustion temperature increases while changing the abovementioned operational characteristics, the NO_x formation also increases in the cylinder. Moreover, NO_x tailpipe emissions are affected by the characteristics of the exhaust after-treatment system (position, volume, light-off performance), the TWC for the vehicles tested.

The NO_x emissions over the NEDC were lower for both vehicles when the high ethanol content E85 was used, compared to the E5. In order to understand the effect of ethanol content in the fuel on NO_x emissions, the results presented in Fig. 1 should be compared with the respective results over the CADC, presented in Fig. 5: For V1 the NO_x reduction with E85 was consistent over both cycles (NEDC and CADC). On the contrary, V2 exhibited increased NO_x emissions over the CADC (both rural and motorway part) with E85. This suggests that NO_x emissions are mainly affected by the operational engine characteristics, as mentioned over the previous paragraph, varying from cycle to cycle and from vehicle to vehicle, rather than by the ethanol content of the fuel [21,22]. More analysis on NO_x emission performance can be found in Section 3.1.2.

Fig. 4 shows the CO, total HC and NO_x average emission performance over the NEDC (Fig. 4a) and the UDC (Fig. 4b) at low temperature conditions (−7 °C). The same scale is used for both cycles, for a direct comparison. The results obtained over the EUDC are not shown, since the emissions for all the vehicle/fuel combination were low (maximum 0.18, 0.28 and 0.23 g/km for CO, total HC and NO_x respectively) compared to the results referred to the UDC. In other words, the CO, HC and NO_x emission levels over the NEDC at −7 °C were dominated by the urban part of the cycle due to the cold-start effect.

The Euro 4 certified V2 complied with the Type VI emission limits (shown also with solid lines in Fig. 4b) for both regulated pollutants (CO and total HC), when operating on E5. The average CO level with E75 resulted instead to be 15.6 g/km, above the current legislated limit for Euro 5 vehicles, while the total HC emissions

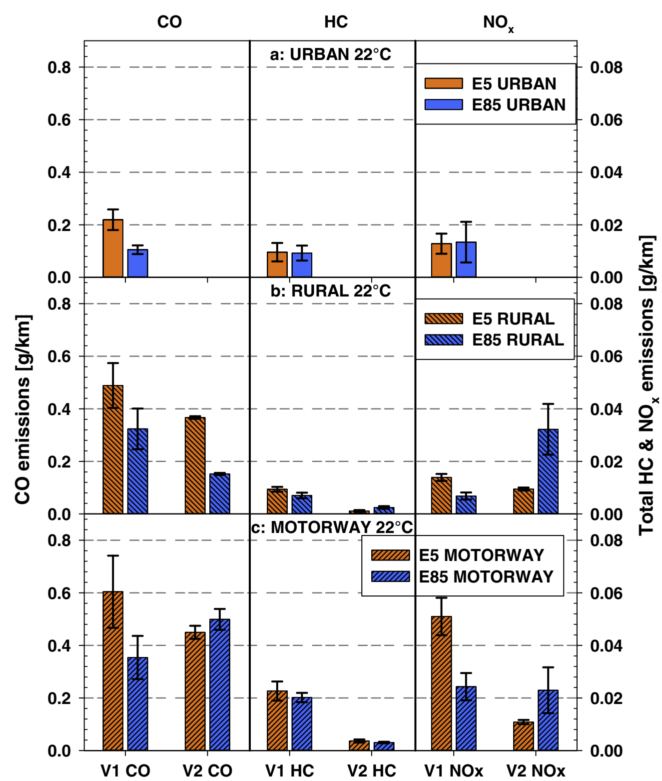

Fig. 5. CO, total HC and NO_x average bag emission values over the Common Artemis Driving Cycle (a) Urban, (b) rural and (c) motorway at 22 °C for the vehicles tested with E5 and E85 fuels. Error bars: standard deviation of average measured values.

remained below the current 1.8 g/km limit (result: 0.95 g/km). CO and total HC V2 emissions increased by 91% and 45% respectively over the UDC when operating on E75, compared to E5.

The Euro 5 V1 showed similar performance in terms of CO emissions with both the test fuels (E5, E75) in the Type VI test (−7 °C, UDC). On the contrary, the total HC emission level increased by 54% with the E75 (resulting: 1.47 g/km), but remained below the current limit (1.8 g/km). Such different trend for CO and HC emissions at low temperature conditions has been also reported in other studies [7,8]. These results clearly depend on the engine technology/calibration and TWC performance when operating on high ethanol blends. More specifically, the legislation required the Euro 4 FFV to be certified in the Type VI test (−7 °C) with pure gasoline only (E0). The performance of the Euro 5 V1 of this study showed that the technology to meet the low temperature test requirements with the use of E75 fuel exists.

3.1.2. CADC results

Fig. 5 shows gaseous emission levels for each combination of vehicle/fuel tested over the CADC cycle at 22 °C. The same scale is used for all the cycle parts for a direct comparison. The average gaseous emission values and the standard deviation of the average values over the CADC Urban, Rural and Motorway for V1, and over the Rural and motorway part for V2 can be found in the Supplementary Material (Table S2). V1 exhibited reduced CO and NO_x emissions when tested with the high ethanol blend E85, in line with the respective NEDC results. Since the specific cycle was run hot-start, no cold-start effect could be identified over the urban part (data available only for V1). The elevated gaseous emissions over the motorway part, compared to the respective results over the EUDC at the same test temperature (Fig. 1c) could be attributed to the more aggressive driving pattern of motorway CADC, compared to the smoother EUDC. Increased CO emissions of FFVs over the CADC motorway were also reported by other studies [7,8]. Under such high speed/flow-rate "real-world" driving conditions the gaseous emission performance depends on the engine calibration (e.g. air/fuel ratio) and on the exhaust after-treatment system characteristics (TWC volume, precious metal loading, etc.). For both vehicles the total HC emissions were again unaffected by the fuel used, as already reported for the NEDC (22 °C).

Fig. 6 shows the evolution of the NO_x instantaneous cumulative mass emissions over the CADC Motorway part for V1 and V2 at 22 °C for both E5 and E85 fuels. V1 exhibited superior performance with E85, compared to E5. On the contrary, V2 showed the opposite behavior, denoting that the evolution of the NO_x emissions is affected by other factors (e.g. cycle, engine calibration, TWC characteristics) rather than by the fuel's ethanol content.

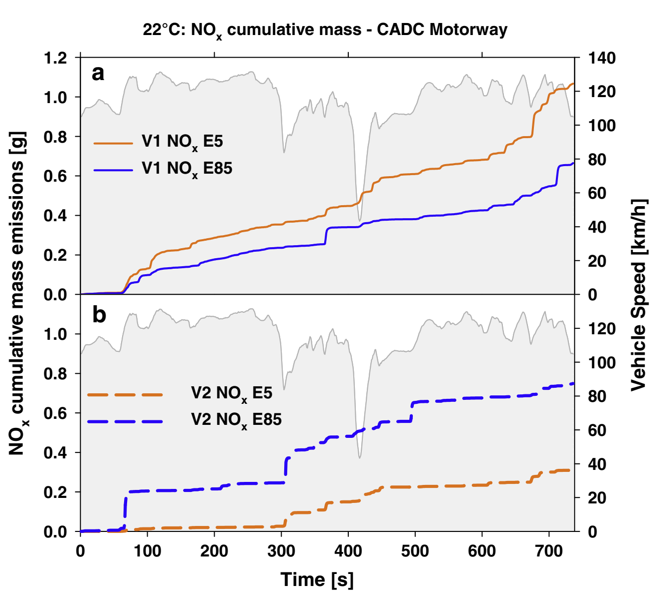

Fig. 6. Instantaneous NO_x tailpipe cumulative mass emissions for (a) V1 and (b) V2 over the Common Artemis Driving Cycle (CADC) motorway part for fuels E5 and E85 at 22 °C.

The emission results over the CADC at −7 °C were higher than the respective values at 22 °C. The main reason was the increased dynamometer settings, simulating the increased friction at low temperature conditions. The more dynamic driving pattern of CADC, compared to the NEDC, enhanced the increase of the emissions between the two temperature conditions over all the three CADC parts. Moreover, since the CADC is a hot-start driving cycle, no cold-start effect could be identified over the urban part, even at −7 °C. The detailed results are presented in the Supplementary Material, Table S2.

3.2. CO_2 emissions and fuel-energy consumption over certification cycle

The recent European regulatory framework sets limits for average CO_2 emissions for each manufacturer [23]. Failure to comply leads to a monetary compensation by the manufacturers. As a consequence, any factor, including fuel quality, influencing CO_2 emissions in the certification test becomes very important. Fig. 7 shows the CO_2 emissions, the Energy Consumption (EC) and Fuel Consumption (FC) of the vehicle/fuel combinations tested over the NEDC at 22 °C.

The use of the E85 caused a reduction of CO_2 emissions by 5.7% and 4.3% for V1 and V2 respectively. Such reduction can be explained considering the quantity of CO_2 per each liter of fuel burned stoichiometrically: as can be calculated from the figures of Table 2, each liter of E85 contains approximately 39% less CO_2 compared to E5. On a mass basis, this is equal to a 2.11 kg CO_2/kg fuel E85 instead of 3.11 kg CO_2/kg fuel E5 (Table 2). The increased fuel consumption (32% on average) partially counterbalances this effect resulting in a direct benefit of approximately 5% in CO_2 (1.39/1.32–1 = 5.3%) of the vehicles which validates the average CO_2 reduction measured for the two vehicles. This CO_2 reduction measured over the NEDC was in line with other studies [7].

The volumetric fuel consumption calculated from the carbon balance for V1 and V2 running on E85 was respectively 31.6% and 33% higher compared to E5. The difference is attributed to the lower heating value per volume unit of E85. As presented in Table 2, 1.35 l of E85 are required for providing the same amount of energy as one litre of E5. Thus more fuel has to be injected in order to cover the same energy demand over the driving cycle. In fact, as will be discussed below, there appears to be a reduction in the energy consumed with E85, as the increase in volumetric fuel consumption was only 31.6% and 33% compared to the 35% which would be necessary for providing the same amount of fuel energy content. This suggests a reduction in energy consumption in the order of 2% which points to a more efficient engine operation with the high ethanol blends.

Indeed, energy consumption with E85 for V1 and V2, was calculated to be lower by 2.6% and 1.5% respectively compared to E5.

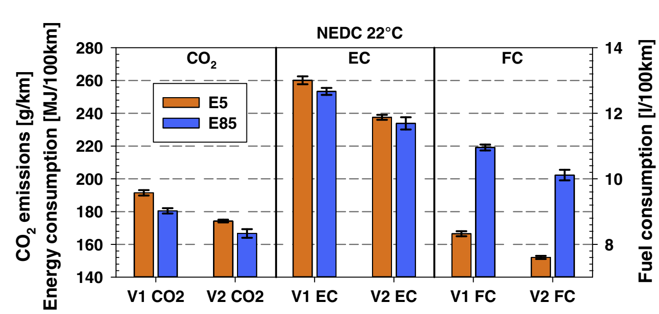

Fig. 7. CO_2, Energy Consumption (EC) and Fuel Consumption (FC) average values over the New European Driving Cycle (NEDC) at 22 °C for the vehicles tested with E5 and E85 fuels. Error bars: standard deviation of average values.

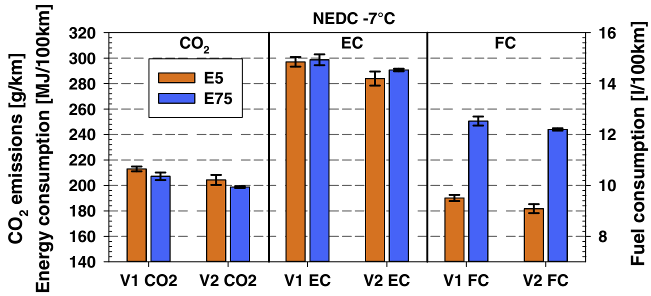

Fig. 8. CO_2, Energy Consumption (EC) and Fuel Consumption (FC) average values over the New European Driving Cycle (NEDC) at −7 °C for the vehicles tested with E5 and E75 fuels. Error bars: standard deviation of average values.

This implies an overall higher efficiency of the vehicle's powertrain over the cycle. There are many factors which can explain such behavior. Firstly, it is possible that the powertrain operation is optimized by the vehicle manufacturer for operation with high Ethanol content fuels. In this sense it is possible that the factors affecting combustion are calibrated to accommodate and exploit the different characteristics of the fuels. Changes in the spark advance for example could trigger combustion over conditions of higher pressure, thus higher combustion rates, which in general increase thermal efficiency. Due to the high oxygen content of E85, the leaning effect on the air/fuel ratio has to be taken into account which might also lead to increase in the thermal efficiency. Finally, ethanol has high heat of vaporization. The vaporization of the fuel absorbs heat from the engine components (combustion chamber and/or intake manifold), thus lowering their temperature. This could improve engine efficiency by reducing pumping losses, as the same amount of air can be introduced in the engine at a lower engine speed/load regime. Detailed investigation on an engine test bench would be required for accurately tracing the origin of this apparent improvement of the engine's efficiency. It should be also noted that this increase in efficiency was not observed over colder operating conditions, fact which rather points to the management/calibration of the engine at different operating conditions.

The CO_2, EC and FC results for the tests conducted at low temperature (−7 °C) are shown in Fig. 8. The CO_2 emission reduction with the use of E75 versus the E5 over the NEDC for V1 and V2 resulted to 2.7% for both vehicles. The lower potential of CO_2 reduction under low temperature conditions can be attributed mainly to two reasons: At −7 °C tests E75 was used, instead of E85 (22 °C), which denotes different fuel properties. This is evident over the hot EUDC part, where the V1 CO_2 reduction was 5.3% at 22 °C (E85 vs E5) and 4.2% at −7 °C (E75 vs E5) respectively. The second reason is the higher fuel enrichment is required with E75 than with E5, at −7 °C during the cold-start UDC cycle part. In this case, the V1 CO_2 reduction was 6.3% at 22 °C (E85 vs E5) and only 1.1% at −7 °C (E75 vs E5), behavior denoting different engine calibration under low temperature conditions.

Similarly to the lower CO_2 reduction at −7 °C tests, energy consumption, resulted to be practically equal for both fuels. Thus, the apparent increase in efficiency over the tests performed at 22 °C was not observed at −7 °C, at least over the cold start sub-cycle. Such findings are in line with other studies over the same cycle and temperature conditions [6].

3.3. Overview and comparison with existing emission factors for Europe

In this paragraph a short analysis and discussion of the overall impact of ethanol blendstocks on pollutant emissions is attempted, together with a comprehensive comparison to existing emission factors used in Europe for FFVs.

Emission results retrieved for each pollutant over each driving cycle were normalized against the average baseline emissions (=1) recorded for the particular pollutant over the same driving cycle. Normalization eliminated the effect of the driving cycle dynamics and provided a basis for a more global comparison of each fuel's impact. In addition, this approach expanded the initial pool of data, allowing for a more accurate statistical analysis of the observed differentiations. Two tailed, *t*-tests were performed between the baseline results and those of the various ethanol blends in order to calculate the statistical significance of the observations. In most cases, it was observed that on a 95% confidence interval, the null hypothesis (H_0) of $\mu = \mu_0$ (where μ the average normalized value) can be rejected, thus there was a statistically significant difference of vehicle emissions. Only hot cycles (EUDC and CADC) were considered in this analysis, the results of which are summarized in Fig. 9. A more thorough investigation of the impact of cold start can be found in [16].

According to previously published studies, the impact of high ethanol blends on emissions from gasoline vehicles is vehicle specific [24–26]. The general trends observed, as discussed earlier in the text, were similar for both vehicle models, but some unique behaviors (e.g. in the case of hydrocarbons) were identified in each one of the two vehicles.

The use of ethanol blends on both vehicles and over both temperature conditions resulted in reduction of CO_2 emissions, which ranged between 2.5% and 8% (Fig. 9a). CO_2 savings were higher over warmer ambient temperatures and for the Euro 5 V1 compared to the Euro 4 V2 suggesting an overall optimized performance of V1. The reduced CO_2 of V1 was accompanied also by a reduction in tailpipe NO_x emissions (Fig. 9b) contrary to the performance of V2 where NO_x consistently increased with the ethanol blends, as also shown in Fig. 5. The increase was more intense with the application of E85 leading to approximately 2.5 times higher NO_x emissions when operating at 22 °C and 1.5 times higher NO_x when operating at −7 °C.

Total HC, NMHC and CO emissions presented a mixed picture (Fig. 9c–e). A consistent reduction of CO was observed with the statistical analysis suggesting in all cases enough evidence to reject the null hypothesis of $\mu = \mu_0$ (emissions equal to baseline). The picture was different with respect to NMHC and total HC where statistically significant differences were recorded in several but not all of the cases (emissions not affected by fuel), and important increase occurred over low ambient temperatures between E5 and E75. In the latter case, emissions increased by a factor that exceeded 10. An interesting observation is related to the impact of E85 on V2 (Euro 4). E85 led to significantly increased total HC emissions while it appears to have a neutral effect on NMHC emissions, fact which points to an increase in methane emissions. In general reduction in CO and hydrocarbons were expected with the application of ethanol [26] whereas some reports also suggest increases in methane emissions when operating on ethanol [27,28].

The observations discussed above are summarized in Table 4. For deriving the impact of the test fuel on each criterion pollutant, the differences in emissions compared to the reference fuel (E5) which were found to be statistically significant were considered as were measured whereas the rest were considered to be zero. The last column of the table contains the proposed correction factors for the emissions of E85 fueled vehicles, compared to those of their gasoline equivalents, which are used for emissions calculation according to the European Monitoring and Evaluation Programme/European Environmental Agency (EMEP/EEA) methodology [29]. The methodology is one of the most widely used methodologies for road transport emissions calculation in Europe. It includes emission factors and relevant transport activity data to

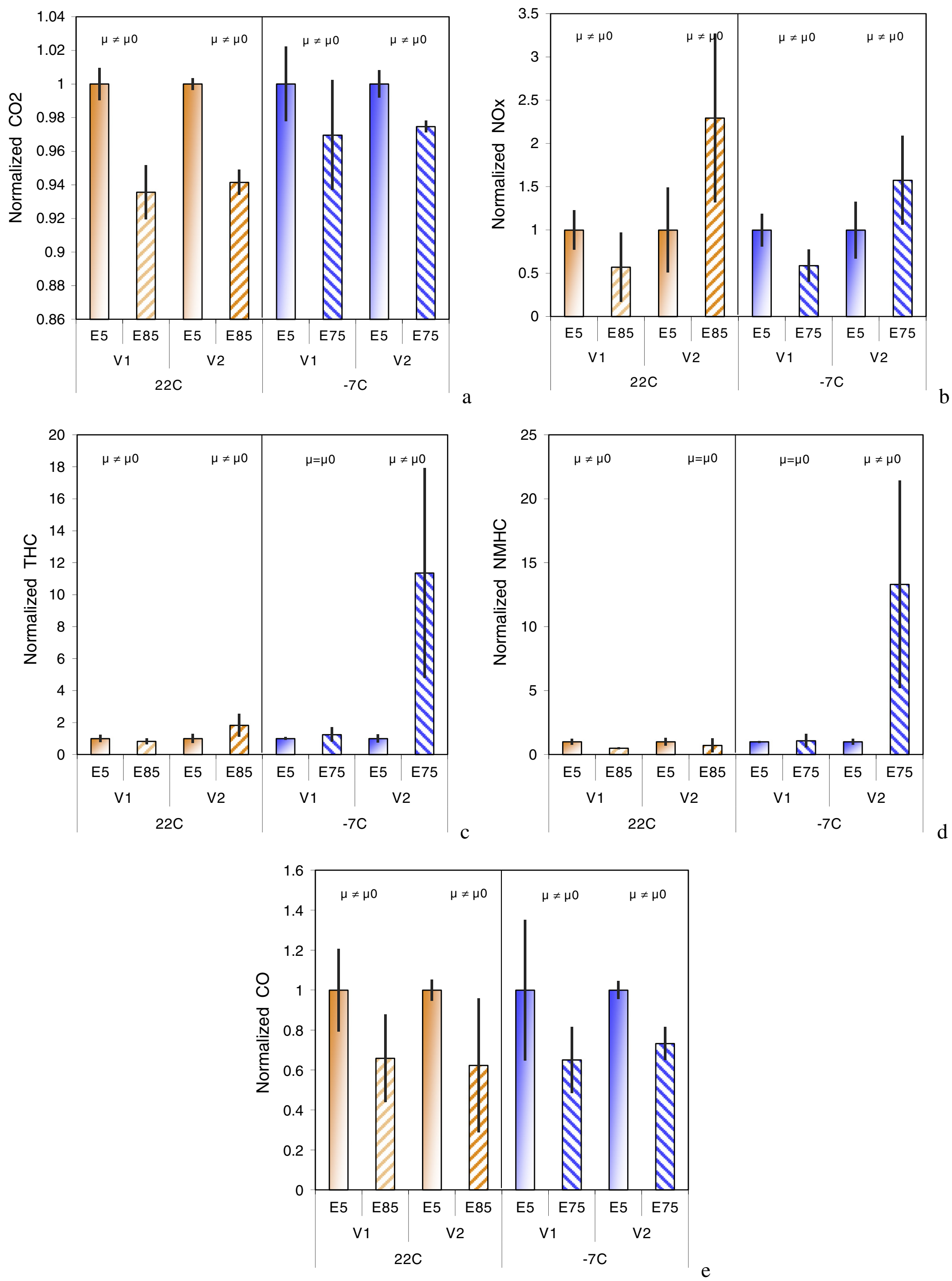

Fig. 9. Normalized emissions over hot start cycles for (a) CO_2, (b) NO_x, (c) total hydrocarbons, (d) Non Methane Hydrocarbons (NMHC), and (e) CO. Error bars correspond to $\pm\sigma$. Indications $\mu \neq \mu_0$ and $\mu = \mu_0$ correspond to the results of the *t*-tests performed between the results obtain with E5 and E75/E85 testing the null hypothesis of $\mu = \mu_0$ on a 95% confidence interval.

enable exhaust emissions from road vehicles to be calculated in European countries. The proposed correction factors are directly applied on existing emission factors for gasoline passenger in order to reflect the expected impact of ethanol blendstocks on vehicular emissions. In Table 4 the correction factors are compared against the measured impact. According to the methodology the respective correction factors are applicable to post Euro 4 FFVs.

As shown, the results of the measurements performed are in line with the trends suggested with regards to CO_2 (decrease), CO (decrease), volumetric FC (increase) and NO_x (decrease). Contrary to the suggested decreases, hydrocarbons appeared increasing in most cases but as discussed previously in this paper over cold start conditions, which are mostly important as the majority of emissions occur over the cold start phase, a rather neutral effect was observed.

4. Conclusions

The paper analysed the regulated gaseous emission performance of two ethanol Flex Fuel Vehicles, tested over the cold-start

Table 4
Summary of the impact of each fuel on emissions. Last column provides a comparison with the corresponding correction factors proposed by the EMEP/EEA methodology for post Euro 4 FFVs.

Vehicle	V1		V2		EMEP/EEA [29] proposed effect of post Euro 4 vehicles (%)
Ambient temperature (°C)	22	−7	22	−7	
Fuel	E85 (%)	E75 (%)	E85 (%)	E75 (%)	
CO_2	−6	−3	−6	−3	−6
Total HC	−17	0	83	1036	−25
NMHC	−50	0	0	1231	
CO	−34	−35	−38	−27	−50
NO_x	−43	−41	129	57	−6
FC (l/100 km)	31	30	27	31	38

New European Driving Cycle and over the hot-start Common Artemis Driving Cycle at two ambient temperature conditions (22 °C & −7 °C). A Euro 5 compliant, direct injection vehicle (V1) and a Euro 4 Port Fuel Injection vehicle (V2) were used in the study.

The measurements showed that at regular ambient temperature conditions (22 °C) CO emissions decreased for both vehicles over both tested driving cycles when the high ethanol fuel blend was used, compared to E5. Total HC emissions were practically unaffected by the fuel type. NO_x emissions decreased for both vehicles (NEDC), while over the CADC the vehicles exhibited different NO_x behavior. Over the low temperature tests at −7 °C both CO and total HC emissions increased with the use of the high ethanol content fuel (E75), compared to E5. However, the Euro 5 V1 exhibited a much lower CO increase than the Euro 4 V2 and emission levels below the current legislated limits for both CO and total HC over the cold-start urban part of the cycle, showing that the technology to meet the low temperature test requirements with the use of E75 exists. Nevertheless more emphasis needs to be given to emissions tests over subzero conditions taking also under consideration the indications presented in [16] by Clairotte et al. that increased ethanol contents in the fuel may lead to increases in organic compounds that act as ozone precursors and the formations of other pollutants that may pose significant health risks. Given the increasing share of ethanol in commercial gasoline fuel, more thorough analyses should be performed to fully quantify the environmental and health impacts of this transition, particularly to northern European and American regions with harsh winter conditions.

Regarding the tools used for emissions monitoring and inventorying in Europe, comparison with existing emission factors for ethanol fuel vehicles showed that results were in accordance with the general behavior for CO_2, CO, volumetric fuel consumption and NO_x. On the other hand, hydrocarbons appeared increasing in most cases. Existing emission factors appear to adequately reflect the performance of such vehicles at warm ambient temperature conditions. Further tests are necessary for generating representative emission factors for ambient temperatures below zero degrees centigrade and facilitate the quantification of the Environmental impact of flex-fuel vehicle introduction and in general the effects of the introduction of ethanol in commercial gasoline fuel.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fuel.2014.09.085.

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