NEN

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Abstract

The aim of the present work is to answer to the Task 3 of the E20/E25 technical evaluation study under agreement between the Commission of the European Union and the European Standardization Committee, CEN (ENER/C2/GA/449-2012/SI2.641582). The work is dedicated to measure on spark ignited vehicles the pollutant emissions (regulated and non-regulated) and fuel consumption when running with different ethanolated fuels. The work was carried out with 2 recent (Euro 5) vehicles: a Peugeot 208 and a Volkswagen Golf 7, on NEDC and WLTC cycles, on standard pollutant emissions as well as CO_2 and benzene emissions.

Five fuels were used to the fuel matrix from 5% to 25% of ethanol volume in gasoline bases, with different blending strategies: E5, E10 (RON95), two splash blends with E10 as gasoline base (E20sb and E25sb) and one blend with a targeted value of octane number and a controlled ratio of ethanol, E20-RON95. The results have shown that all formulated fuels respect the EN 228 standard, even the splash blended E20sb and E25sb.

For both cycles and vehicles the EURO 5 emission limit is respected. EURO 5 Pollutant emissions limits are also respected on WLTC, except for CO emissions of Peugeot vehicle for fuels containing less than 20% of ethanol. Ethanol had a positive impact for vehicles which high CO emissions. Indeed, adding ethanol seems to favours the CO emission reduction and has consequently a strong potential for real-life pollutant emissions. This is also the case for particles number and mass where a positive impact of ethanol was observed by reducing particles emissions especially for direct injection technology. For HC, there is a slight decrease of emissions when adding ethanol. Also, there is a clear cycle effect with emissions of NEDC cycles higher than WLTC ones. In the case of NOx, ethanol seems to have a negative effect since it slightly increase with higher ethanol volumes. Nevertheless, NOx emissions remain extremely low; they respect EURO 5 and even EURO 6 standards for both vehicles and on WLTC with all fuel matrix tests. As expected, fuel consumption raises when net calorific values decrease. Ethanol content presents no significant impact on CO_2 for Golf; and only a limited impact for Peugeot with the reduction of CO_2 by increasing ethanol which is not surprising as, firstly conventional vehicles (without ethanol detection and optimisation strategies) have been used and, secondly CO_2 emissions is directly linked to H/C ratio meaning linked to the chemistry of the fuel base and also to the ethanol content of the fuel. The last point of this study is that higher ethanol content seems to favours the reduction of benzene emissions at exhaust gases which is due to a dilution effect.

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1 Introduction

In 2011, a consortium of DG Joint Research Centre, EUCAR and CONCAWE published a set of scenarios that considered the potential of the European vehicle fleet to consume biofuel to year 2020. The consortium then compared these scenarios with the 2020 renewable energy target for transport of the Renewable Energy Directive (RED) and the 2020 greenhouse gas (GHG) target for road transport fuels of the Fuel Quality Directive (FQD). The scenarios demonstrated the difficulty in meeting the targets with the existing limitations for biofuel in the specifications for mainstream fuels (petrol and diesel). Therefore, additional scenarios were included in which higher biofuel blend rates were considered, including the introduction of E20 in years 2015 and 2017. The update of this study, released in early 2014, still considers E20 as an important driver of biofuel introduction, with an introduction of E20 in the market in 2019, in 2 of the 4 considered scenarios.

Subsequently, CEN/TC 19/WG 38 “New fuels coordination and planning” decided to develop its own report on the technical issues associated with the introduction of what are described as “E10+ fuels”, with a particular focus on E20 to E25 (hereinafter referred to as “E20/25”). ePURE (European Renewable Ethanol Association) members are participating in this project alongside experts from the oil and auto industries and related fields.

At the same time, a task force under the auspices of CEN/TC 19/WG 21 “Specification for unleaded petrol” is presently developing a European standard for ethanol fuel for blends up to 85% with petrol. This is intended to define a “one-fits-all” specification for ethanol fuel in blends with petrol for existing fuels in Europe. Serendipitously, it would provide the oil and auto industry with a clear understanding of ethanol quality for future fuels such as E20/E25. Again, ePURE and some of its members are participating in this project alongside experts from the oil and auto industries and related fields.

The aim of the present work is to answer to the Task 3 of the E20/E25 technical evaluation study under agreement between the Commission of the European Union and the European Standardization Committee, CEN (ENER/C2/GA/449-2012/SI2.641582), by measuring on dedicated vehicles the pollutant emissions (regulated and non-regulated) and fuel consumption when running with different ethanolated fuels.

The work was carried out around the test of 2 vehicles on NEDC and WLTC cycles, with standard pollutant emissions measurements, but also unregulated pollutant emissions. The vehicles tested were a Golf 7 and a Peugeot 208.

2 Operating Conditions

2.1 Fuel Matrix

The matrix aims to study fuels blends likely to fulfil ethanolated fuels quality of future fuels blends. The tests were led around 4 fuels and 1 reference fuel, based on the matrix below (Table 1). Ethanol content varies from 5%v/v up to 25%v/v.

Fuel E5 is the one used for the homologation process of Euro 5 standards for vehicles; it is here considered to be representative of fuels found in the market. E10 fuel was formulated in order to achieve a vapour pressure of 60kPa (upper limit of summer grade for France, class A of European EN 228 specification) and a RON of 95.

Two fuels were obtained by splash blending, hereafter named “sb”, which consists to direct mixing ethanol to gasoline base. The fuel E10 was used as gasoline base fuel for the splash blending fuels E20sb and E25sb. Fuel E20RON95 was formulated according to the target to achieve a RON of 95 and it is considered as fuel for standard Euro 6 tests, its results will be compared to E20sb fuel. Thus, it is important to notice that **both E20 (sb and RON95) do not have the same gasoline base.**

Table 1. Fuel matrix

Fuel n°	Notation	Formulation	Standard
1	E5	5%v/v of ethanol (Euro 5 reference fuel)	EN 228
2	E10	10%v/v of ethanol with a target vapour pressure of 60kPa and RON of 95	EN 228
3	E20sb	Splash blend with E10 as base fuel	---
4	E20RON95	20%v/v of ethanol and a target RON of 95	*EN 228**
5	E25sb	Splash blend with E10 as base fuel	---

**except for ethanol content*

On the other hand, **it is also important to notice that fuels E10, E20sb and E25sb have the same gasoline base.**

2.2 Fuels Properties

Ethanol blending in gasoline will impact some physical properties, especially the vapour pressure and distillation profile, due to the formation of azeotropes. It is important to mention that the pure ethanol have a vapour pressure around 15-20kPa while in standard EN 228 Class A gasoline it is around 50-60kPa.

Table 2 shows the detailed analysis of physical properties of fuels studied. It is observed that all fuels respect EN 228 limits, including splash blending fuels. All fuels respect the summer limit, for the French case, of EN 228 in terms of vapour pressure and volatility. Fuel E25sb is the upper limit of E100.

In terms of chemical composition, there is no detection of MTBE and ETBE for all fuel blends. The octane index, RON and MON, respects the EN 228 standards. All fuels presented around one point higher RON value than the RON target expected (Figure 1).

As this bias occurred to all fuels blends, it will not represent a significant influence on the results interpretation and analysis.

The H/C ratio of E20sb and E20RON95 are different, 2,028 and 2,095 respectively, since they have a different gasoline base.

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Table 2. Detailed properties analysis of fuels matrix

	Unit	Limit (EN228)*		Method	Results				
		Min	Max		E5	E10	E20sb	E20-RON95	E25sb
PHYSICAL PROPERTIES									
Density @ 15°C	kg/m3	720	775	EN ISO 3675-98	752,0	749,4	754,0	753,2	756,3
DVPE @ 37.8°C	kPa	45 summer 60 winter	60 summer 90 winter	EN ISO 13016	58,2	57,6	56,4	56,5	54,9
DISTILLATION									
IBP	°C			ASTM D 86	34	37	40	40	45
10%Vol	°C			ASTM D 86	48	52	56	57	57
20%Vol	°C			ASTM D 86	51	60	61	60	62
30%Vol	°C			ASTM D 86	56	63	65	68	66
40%Vol	°C			ASTM D 86	63	67	68	70	69
50%Vol	°C			ASTM D 86	83	87	70	72	72
60%Vol	°C			ASTM D 86	99	102	73	75	74
70%Vol	°C			ASTM D 86	107	114	110	113	78
80%Vol	°C			ASTM D 86	116	129	126	125	124
90%Vol	°C			ASTM D 86	134	153	149	154	146
95%Vol	°C			ASTM D 86	180	***	167	172	165
FBP	°C		210	ASTM D 86	198	195	194	190	194
Residue	%Vol		2	ASTM D 86	1	1	1	1	1
E 70°C	%Vol	20 summer 22 winter	48 summer 50 winter	ASTM D 86	35	43	47	40	44
E 100°C	%Vol	46	71	ASTM D 86	52	58	66	63	71
E 150°C	%Vol	75		ASTM D 86	84	89	90	89	91
COMPOSITION									
Ethanol	%Vol			EN 1601	4,8	9,6	18,0	19,2	24,2
Saturates	%Vol			ASTM D 1319	57,5	60,1	55,1	59,8	52,2
Olefins	%Vol		18	ASTM D 1319	5,8	5,1	2,9	2,7	2,7
Aromatics	%Vol		35	ASTM D 1319	31,8	25,2	23,7	17,9	22,4
Benzene	%Vol		1	EN 238	0,1	0,429	0,388	0,372	0,367
OCTANE INDEX									
RON	index	95		ISO 5164	97,5	95,8	98,3	96,2	99,4
MON	index	85		ISO 5163	87,1	85,7	85,4	85,2	85,8
COMBUSTION									
Net calorific value in mass	kJ/kg			ASTM D 240 / Calculated	42199	41990	40355	40380	39475
Net calorific value in volume	kJ/L			Calculated	31734	31467	30428	30414	29855
%C	%Mass			GC	85,00	82,91	79,82	78,32	78,28
%H	%Mass			GC	13,20	13,54	13,48	13,66	13,46
%O	%Mass		3,7	GC	1,80	3,55	6,70	8,02	8,26
O/C				Calculated	0,020	0,032	0,063	0,077	0,079
H/C				Calculated	1,865	1,962	2,028	2,095	2,065

** The limits considered in France correspond to the Summer grade (Class A of EN 228)*

***MTBE and ETBE are not present (0%mass)*

**** E10 95% distillation volume was not acquired*

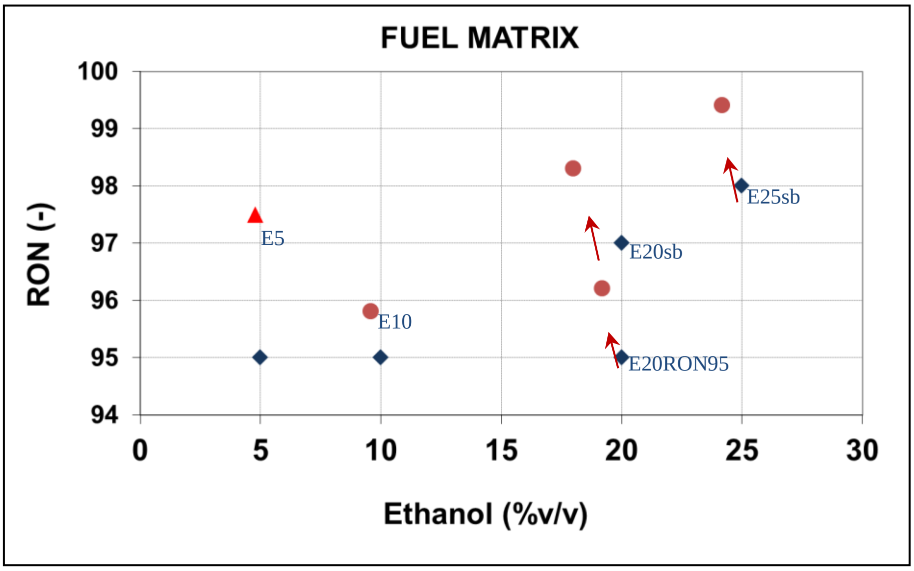


Figure 1. RON data of fuel matrix: (blue) target RON, (red) RON obtained

Figure 2 shows the evolution of fuels distillation curve. The distillation profile shows no significant difference below 40% and more than 80% distillation volume. Between 40 and 80 there is observed a step following the order: E10 < E20sb=E20RON95 < E25. This step is direct linked to ethanol content increase and it is due the boiling point of ethanol which is around 78°C.

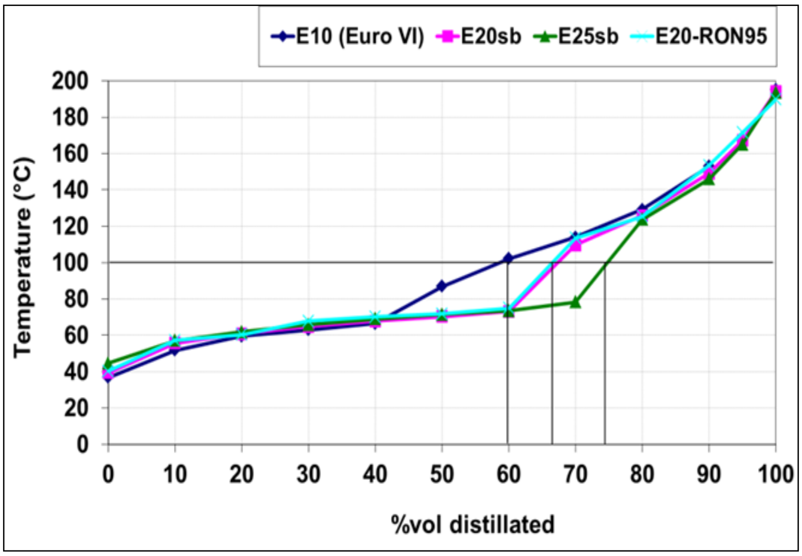


Figure 2. Distillation curve of fuels E10, E20sbn E20RON95 and E25

Figure 3 shows the volatility of fuels according to E70. The volatility profile of fuels from the same gasoline base, increases with ethanol quantity until a maximum achieved with E20sb, after that it decreases. All fuels are into the limits of Class A EN 228 grade (45-60kPa). Figure 4 corresponds to vapour pressure (DVPE for *Dry Vapour Pressure Equivalent*) depending on ethanol content. The DVPE slightly diminishes when adding ethanol. This effect is expected according to the literature [1, 2] (Figure 5, [2]) where it was shown that from E5 to higher ethanol content, the vapour pressure tends to decrease.

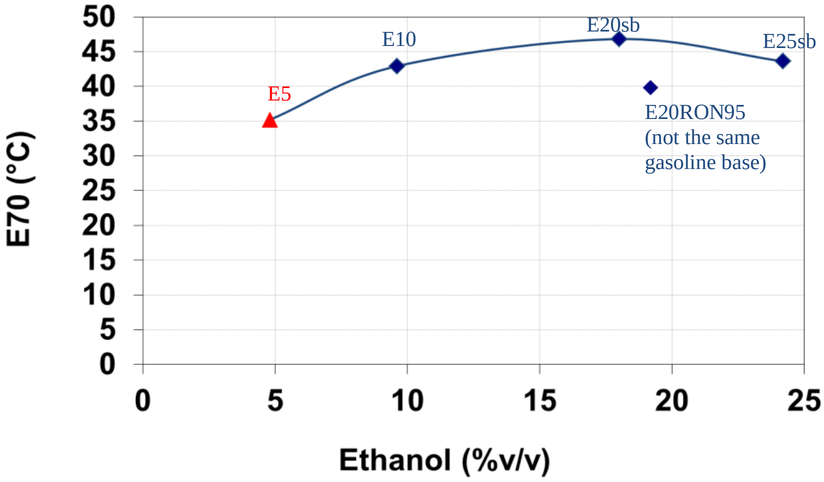


Figure 3. Volatility, E70 data, depending on ethanol content

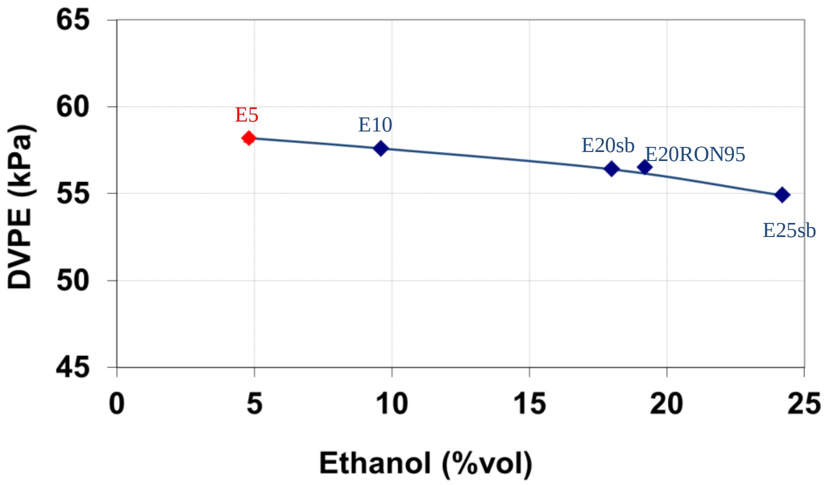


Figure 4. Vapour pressure evolution as a function of ethanol content

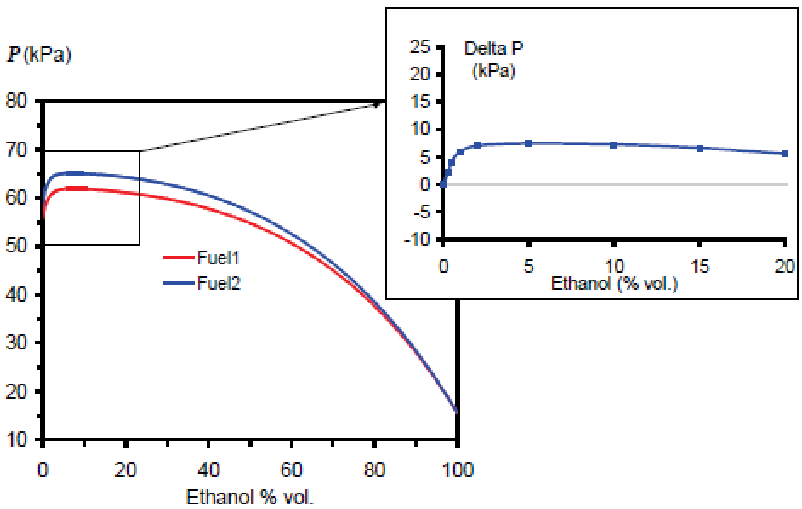


Figure 5. Vapour pressure evolution by ethanol content

The chemical composition is represented on Figure 6 below. The content of saturated, olefins, aromatics and benzene diminishes when the ethanol quantity increases for fuels with the same gasoline base (E10, E20sb and E25sb). This characteristic is due to the dilution of these compounds by adding ethanol in the mixture. By comparing fuels with the same ethanol content but different gasoline base, E20sb and E20RON95, it is observed that the former present lower concentration of saturate and olefins, nevertheless it presents higher aromatic content. Figure 7 presents the benzene content of fuels blends. As before, the benzene concentration decreases when ethanol content increases. The same dilution effect can be considered.

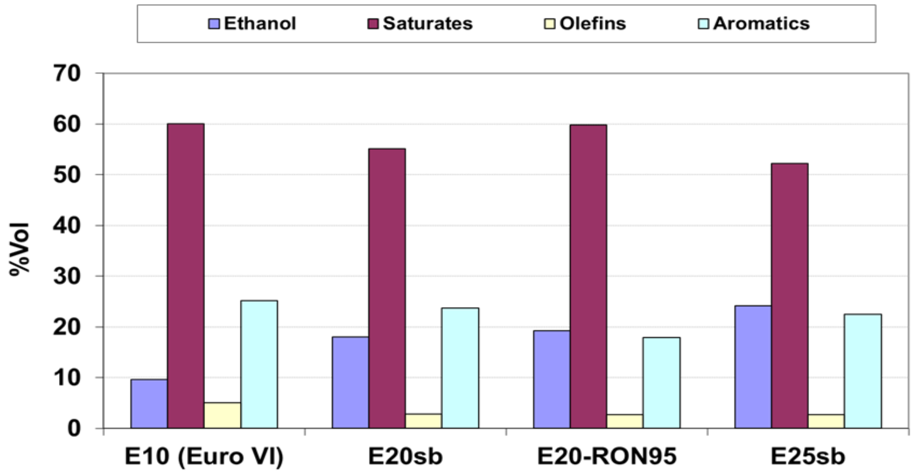


Figure 6. Chemical composition of ethanol/gasoline blends

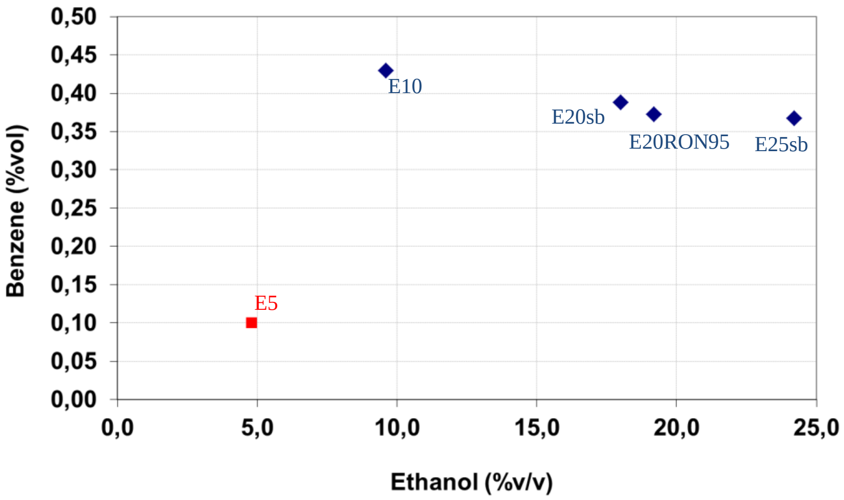
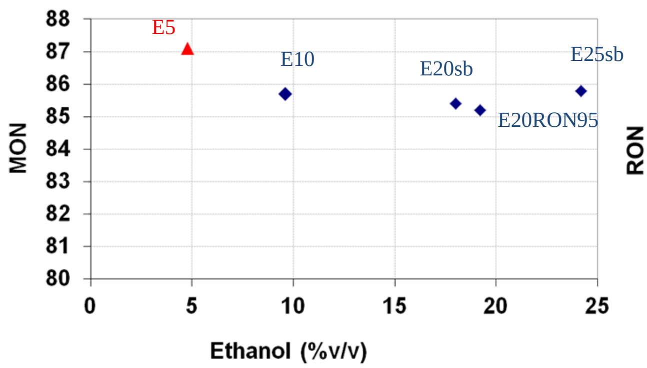


Figure 7. Benzene content of ethanol/gasoline blends

A well-known advantage of ethanol incorporation into gasoline base is the positive impact on the octane index [1]. Two standard octane rating procedures are traditionally used to rate the octane index of fuels: Research Octane Number (RON) and Motor Octane Number (MON). RON and MON are used to characterize spark-ignition engine fuels in terms of their propensity for auto ignition and engine knock. RON simulates fuel performance under low severity engine operation whereas MON simulates more severe operation that might be incurred at high speed or high load. Classically, both numbers are measured using the Cooperative Fuel Research (CFR™) engine as described in ASTM D2699 and D2700, respectively, with variable compression ratio engine. For both RON and MON, the engine is operated at a constant speed (rpm) and the compression ratio is increased until the onset of knocking. Although it is well known that increasing the RON of gasoline there is an increase of MON, the incremental increase in MON is typically only 30-50% of the RON[1].

Ethanol has higher RON and MON (typically ~ 110+ and 90+) than gasoline (95 and 85, respectively) which can be considered as an advantage of ethanol/gasoline blended fuels. Figure 8 shows the RON and MON evolution of fuel blends. For fuels from the same gasoline base, the RON raises linearly from E10 to E25sb. On the other hand, MON values are quite constant. Indeed, the impact of ethanol seems to be more important for RON than MON, this observation has already been pointed out in the literature [3] where the impact of ethanol over MON is lower than observed for RON, especially if measured in terms of volume.



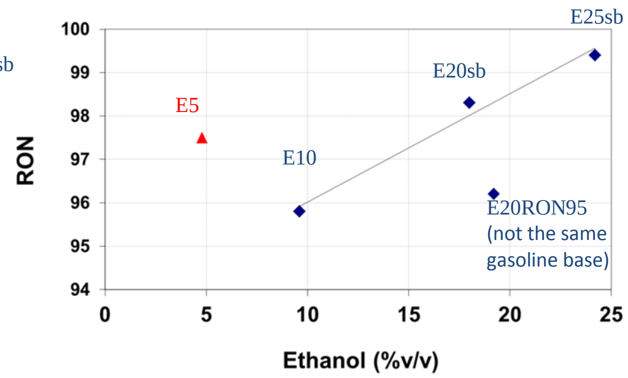


Figure 8. MON (left) and RON (right) results of ethanol/gasoline blends

Density results of ethanol/gasoline blends and their net calorific value in mass and volume are presented on Figure 9 and Figure 10 below. The graph shows an increase of density results when the content of ethanol increases for fuels from the same gasoline base. The opposite is observed for energy content in volume and mass since there is a markedly decrease when risen ethanol content. Here, the energy content drops 5,1% (volume) and almost 6% (mass) from E10 to E25sb. These results will have in impact over fuel volumetric consumption.

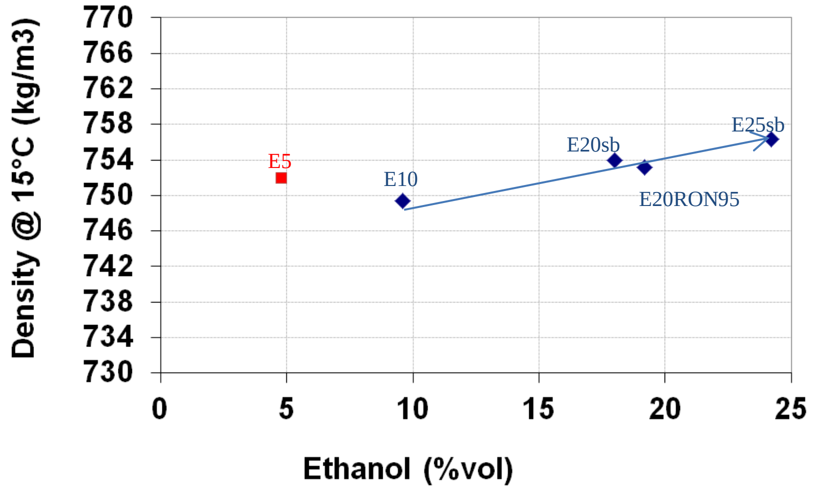


Figure 9. Density variation as a function of ethanol content

1 http://www.refiningonline.com/engelhardkb/crep/tcr4_29.htm

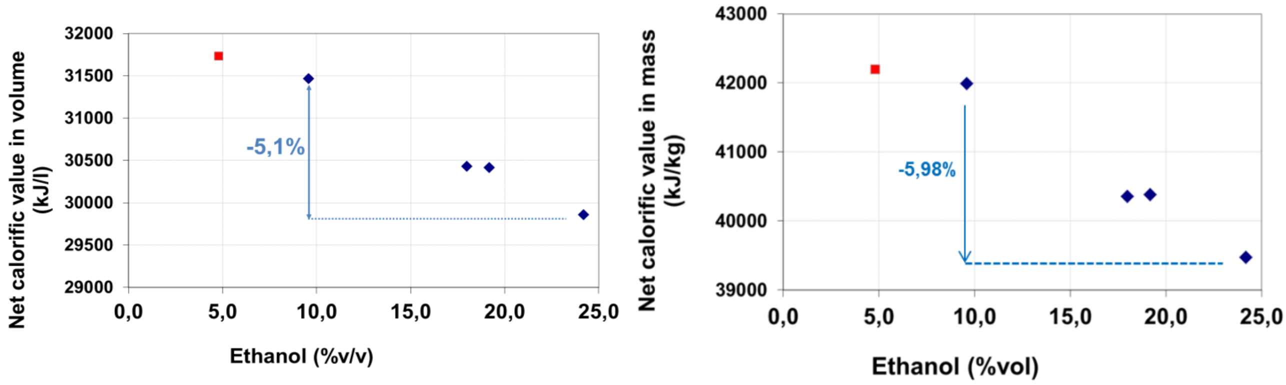


Figure 10. Energy content variation in volume (left) and mass (right) of ethanol/gasoline blends

Main results of fuel matrix:

- ✓ **Fuels E10, E20sb and E25sb have the same gasoline base**
- ✓ **E10 and E20RON95 have the same RON**
- ✓ **Fuel E20RON95 was formulated to have a RON of 95, it does not present a significant difference in terms of vapour pressure, density and energy content than the E20sb**
- ✓ **Fuel E20RON95 presents lower aromatics and higher saturate content than E20sb**
- ✓ **There is an interesting difference between RON values of E20sb and E20RON95, it can have an impact on vehicles tests results**

2.3 Vehicles tests: operating conditions

2.3.1 Introduction to the vehicles

The impact of ethanol content over Engine, Driving cycles, regulated and non-regulated pollutants were carried out with two vehicles, Peugeot 208 and Golf 7 Volkswagen, their main technical data as well as the announced emissions limits are described in Table 3 below. Both vehicles are homologated according to EURO 5 standards, they have recent engine technology, turbocharger system is present only in the Golf 7.

- #1: Peugeot 208, indirect injection

The engine technology VTi (for Variable valve lift and Timing Injection) of Peugeot 208 was performed in collaboration with BMW group, it was launched in the summer 2012. The engine with 3 cylinders in line and Indirect Multipoint Injection system contains 4 valves per cylinder.

- #2: Golf 7, direct injection

Table 3. Technical characteristics of the two vehicles tested: Peugeot 208 and Golf 7 Volkswagen[2]

	Peugeot	**Volkswagen**
Registration date	27/09/2013	04/02/2014
kilometres (before tests)	3170km	3089km
Category	208	Golf 7
Series	1.2 VTi 82ch BVM5	1.4 TSI 140 ACT BlueMotion Technology
Empty weight (kg)	1050	1296
ENGINE		
Max power kW (ch)	60 (82)	103 (140)
Ratio power to weight W/kg	57	79
Engine size (cm3)	1199	1395
Cylinder	3	4
Max torque Nm (m.kg)	118	250
Injection type	Port injector (indirect)	GDI
Supercharger	-	yes
Polluting level	Euro 5	Euro 5
CO_2 emissions 80/1268/CE		
CO_2 (g/km)	104	109
Urban (L/100 km)	5.5	5.8
Extra Urban (L/100 km)	3.9	4.2
Combined (L/100 km)	4.5	4.7
POLLUTANTS EMISSIONS		
CO (mg/km)	691	646
HC (mg/km)	66	41
NOx (mg/km)	27	32

2 References: www.vcacarfueldata.org.uk; www.peugeot.fr; www.volkswagen.fr

The TSI engines correspond to the direct-injection, supercharged engines from Volkswagen. The presence of turbocharger increase the air throughput of the engine by compressing the air required for combustion. By fitting a turbocharger, power, torque and efficiency can be increased compared to a naturally aspirated engine with the same displacement. The BlueMotion technology includes[3]: reduced idle speed, longer ratios for the higher gears, lowered body, energy regeneration and a start-stop system.

2.3.2 Experimental set-up and facilities

The roller bench n° 7 at IFPEN was used to the present work (Table 4) . The roller bench is located into a conditioned chamber maintained at 22°C±1°C. The driver was assisted by a driver aid system to follow driving cycles. Roller rotation speed is controlled electronically. The exhaust gases emission were collected and measured according to the Constant Volume system (CVS) based on a full flow dilution tunnel. Figure 11 and Figure 12 show the schema of roller bench n° 7 and the analytical apparatus linked to it.

Table 4. Roller bench n°7 technical characteristics

Power (kW)	55
Speed (km/h)	160
Type	Bi-roller
Ventilation maximum speed	120km/h
Temperature	22°C ± 1°C
Hygrometry	52% ± 10%

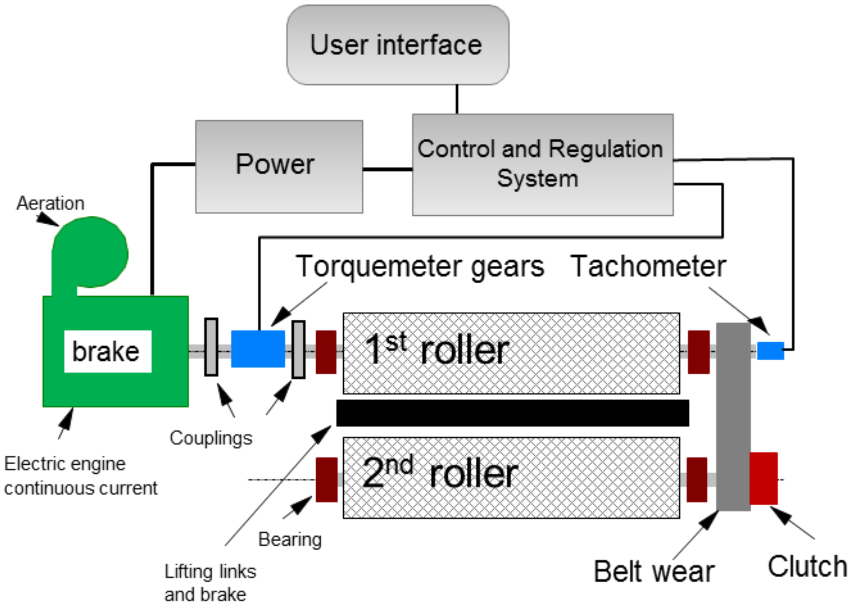


Figure 11. Schema of roller bench n°7

[3] http://en.volkswagen.com/en/innovation-and-technology/technical-glossary/bluemotion.html

The gaseous emissions were collected using tedlar bags and further analysed in terms of regulated and non-regulated pollutant emissions: HC, CO, NOx, CO_2, particles number and mass and benzene. Fuel consumption was monitored as well. The analytical apparatus used is described in Table 5. The main characteristics of particles counter are presented on

Table 6.

Table 5. Analytical methods employed to measure gaseous emissions, particles mass and number

Compound	**Analytical Method**
CO	Non Dispersive Infra-Red (NDIR)
CO_2	Non Dispersive Infra-Red (NDIR)
HC	Flame Ionization Detector (FID)
NOx	Chemiluminescence Analysis (CLA)
Benzene	Gas chromatography-FID (GC-FID)
Particles mass	FilterPallflex
Particles number	CPC (condensation counter)

Table 6. Particles condensation counter (CPC) technical information

Model	**HORIBA** MEXA-2000SPCS
Standard method	UNECE, ECE R83/TRANS/WP.29/GRPE/2008/62; CE, FCC
Particles concentration	0-10000 to 0-50000 particles/cm^3 (after dilution)
Standard configuration	Main unit : volatile particle remover (VPR) 1st dilution level, evaporation tube and 2nd dilution level Particle counter (PNC)
Dilution factor	1st level (PND1) Standard : 10-200 (diluted gas) 2nd level (PND2): 15
Temperature	1st level (PND1): 191 ºC ± 10 ºC Evaporation tube (ET): 350 ºC ± 20 ºC 2nd level (PND2): < 35 ºC
Counter limitation	Efficiency for particles of 23 nm: 50% ± 12% Efficiency for particles of 41 nm: higher than 90%

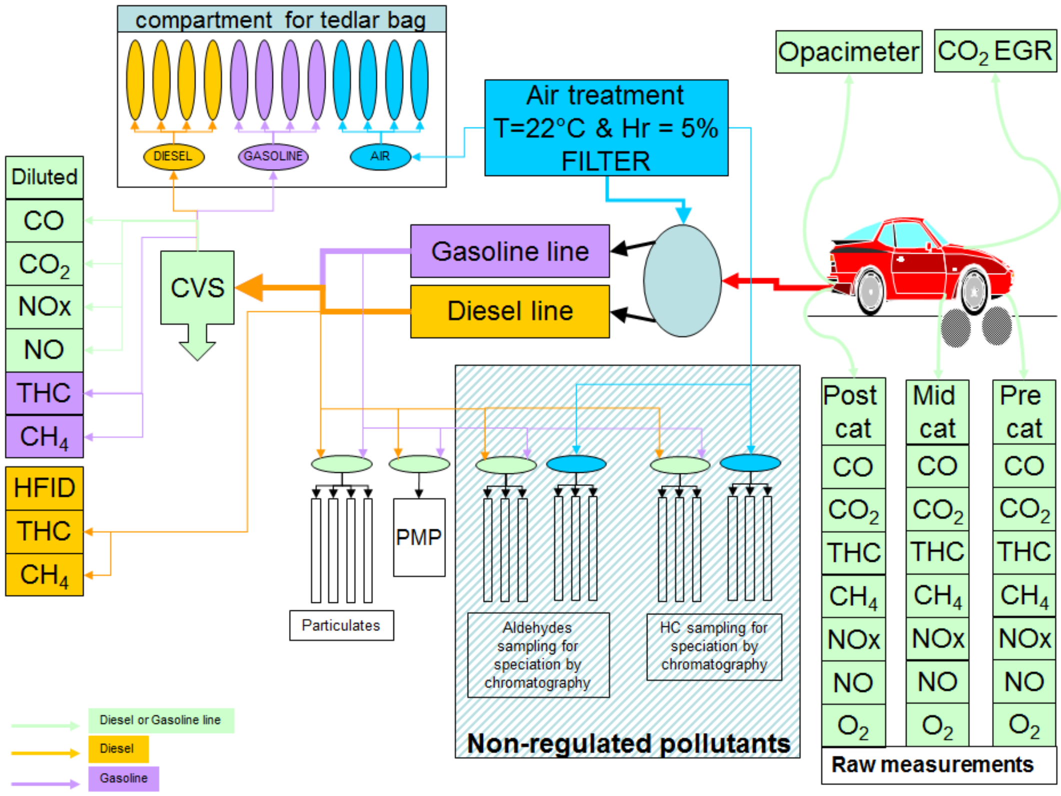


Figure 12. Apparatus available at roller bench n°7

2.4 Vehicles test protocol

2.4.1 Background

Regulated and non-regulated emissions as well as fuel consumption of the test vehicles were measured over two different driving cycles, NEDC and WLTC, which are going to be described in the tests cycles section. The protocol to perform the tests was:

- Introduction of the vehicle in the roller bench according to the standard conditions
- Cold soaking vehicle with temperature between 20°C and 25°C
- Driving test according to NEDC cycle or WLTC cycle

The roller bench, described previously, is able to simulate the resistance applied against the vehicle due to its mass and aerodynamic conditions. To each test the measurement of fuel/air equivalence ratio was obtained as well as the exhaust gas emissions as described in the last section of the present report. The uncertainty of analytical measurements for non-regulated emissions is ±1%. Sampling uncertainty is quite higher and adding this value to the analytical bias, the uncertainty is about ±15%[4].

2.4.2 Test cycles

Regulated and non-regulated emissions as well as fuel consumption of the test vehicles were measured over two different driving cycles:

[4] IFPEN internal data

- New European Driving Cycle (NEDC), which is the legislative cycle for type approval of European passenger cars (see Figure 2). This is a cold start cycle. All of the tests performed using this cycle were carried out after the vehicle had experienced an overnight soaking period. The NEDC consists of two parts: four repeated Urban Driving Cycles (UDC, also ECE-15) and an Extra Urban Driving Cycle (EUDC).
- Worldwide harmonized Light Vehicles Test Cycle (WLTC) is being developed by the UNECE[5] group. It is expected to enter the European procedure for type approval testing of light-duty vehicles in the near future. The WLTC procedure includes different cycles (low, middle, high and extra-high) applicable to vehicle categories of different power-to-mass (PMR) ratio. The sequence of different cycles is not yet completely finalized by the UNECE group.

2.4.3 NEDC cycle

NEDC or NMVEG (for *New Motor Vehicle Emission Group*) profile is presented on Figure 13 and the data associated is shown in

Table 7. The NEDC is used as reference cycle for homologating vehicles until Euro6 norm. It is made of an urban part called ECE, which is repeated four times, and an extra-urban part, named EUDC.

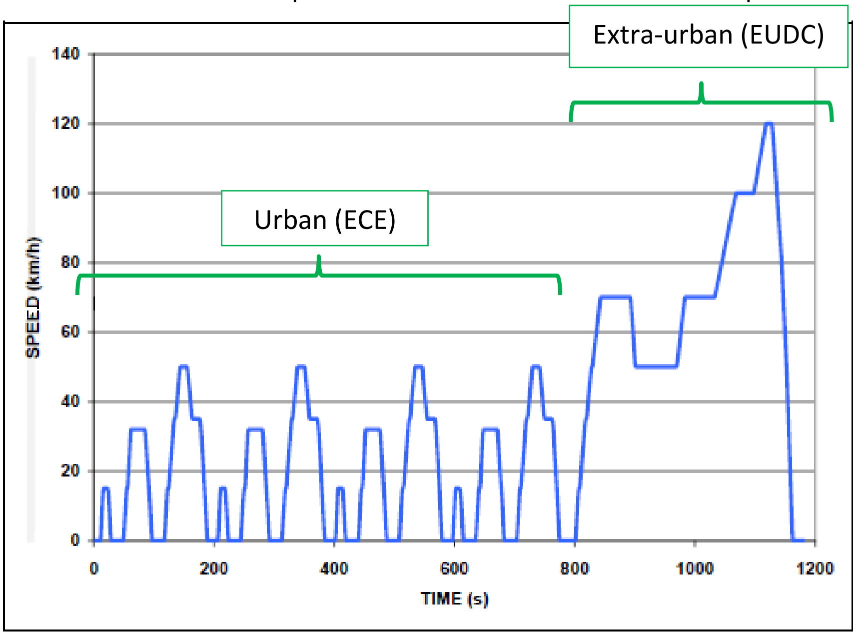


Figure 13. New European Drive Cycle (NEDC)

Table 7. Data associated to NEDC cycles

Cycle	Distance	Temps
ECE unit	1013 km	195 s
EUDC	6955 km	400 s
TOTAL	11007 km	1180 s

5 For *United Nations Economic Commissions for Europe*

2.4.4 WLTC cycle

The WLTC cycle allows evaluating the pollutants and emissions, the fuel economy but also the electric range of light duty vehicles (passenger cars and vans). It is developed by European, Japanese and Indian experts in order to replace the NEDC cycle. In the present study, the four cycles were performed according to version 5 of WLTC cycles proposed by UNECE (Figure 14).

Comparing NEDC and WLTC cycles it is possible to identify clearly the main differences: WLTC cycles are performed on long distance and it takes more time than NEDC (see Table 9). The average speed of WLTC is higher, also there is more time spent in acceleration/deceleration than in stationary phases which leads to WLTC cycle higher power demand.

WLTC cycle is considered as more representative of real driving conditions.

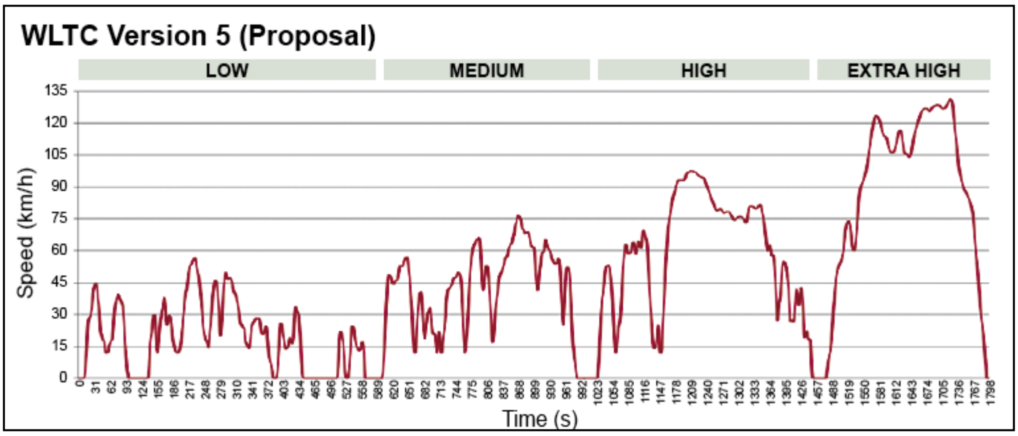


Figure 14. Profile of WLTC cycles (version 5 proposal UNECE)

Table 8. Data associated to WLTC

Cycle	Distance	Time
Low	2980km	590 s
Middle	5008km	433s
High	7015km	455s
Extra-High	7720km	322s
TOTAL	22723km	1800s

Table 9. Comparison WLTC and NEDC cycles

	NEDC [1)]	WLTC
Length (s)	1.220	1.800
Length (km)	11,06	23,26
Idle time (%)	33	13
V_{max} (km/h)	120	131,6
$V_{average}$ (km/h)	31,6	46,3
$Accel_{max}$ (m/sec^2)	1	1,6

[1)] NEDC = New European Driving Cycle - ECE + EUDC

2.5 Standard emissions regulation (Euro 5 and Euro6)

The exhaust emissions regulation Euro 5 and Euro 6 for spark ignition engines is presented on Table 10. It is important to notice that Euro 6 legislation is valid since 2014. The present work uses this data to evaluate the driving cycle's emissions depending on ethanol content into gasoline base fuels.

Table 10. EU emissions legislation for HC, NOx, CO, particles mass and number applied to NEDC cycle

Emissions	**Unit**	**Euro 5 legislation**	**Euro 6 legislation**
HC	mg/km	68	68
NOx		60	60
CO		1000	1000
PM		4,5	4,5
PN#	nb/km	-	*6,0E+11**

**IDE vehicles are authorized until 6E+12 particles number/km.*

2.6 Repeatability criteria of driving tests cycles

The repeatability criteria were defined using CO_2 emissions as the main parameter. The calculation is based on CO_2 measurement over two tests according to the following formula:

$$\mathrm{Re}\,peatability = \frac{2\times\sigma_{CO_2}}{Average\times\sqrt{Nb\_tests}}$$

where σ_{CO_2} is the standard deviation of CO_2 global measurements. A value higher than 1% indicates a low repeatability giving rise to the realization of a third driving test. Only the tests sequence with σ_{CO_2} <1% will be than considered to data analysis.

3 Driving cycles results

The results of driving cycle's emissions are analysed in order to discuss ethanol content impact over regulated and non-regulated pollutant emissions as well as fuel consumption and CO_2 emission. A discussion about fuel/air equivalence ratio is done to evaluate the impact over CO emissions.

All results are presented according to measurements of 2 cycles (NEDC and WLTC) for both vehicles (Peugeot 208 and Golf 7 Volkswagen) as described previously. Detailed testing results are available form the authors.

3.1 Regulated pollutants emissions

3.1.1 CO emissions

Figure 15 shows the average of CO emissions depending on fuel formulation, E5, E10, E20sb, E20RON95 and E25, for both vehicles and cycles. For NEDC results, there is no significant difference of engine technology over CO emissions for all fuels in the matrix, the same is observed for WLTC cycle over Golf vehicle. For these conditions the CO emissions respect the Euro 6 standards and are considerably below 1g/km of CO.

For Peugeot under WLTC cycle it is clearly observed the ethanol content positive impact over CO emissions, the CO emissions about 1,8g/km with E5 fuel drops down to 0,4g/km with E20sb, E20RON95 and E25, corresponding to more than 77% of CO emissions reduction when adding ethanol to gasoline base.

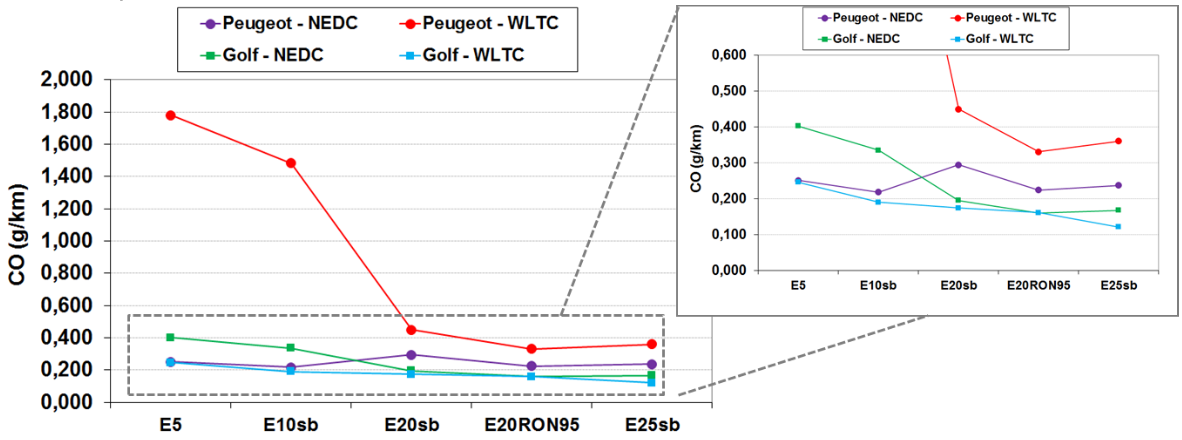


Figure 15. CO emissions in g/km for NEDC and WLTC cycles for golf and Peugeot as function of ethanol content from E5 to E25sb

Figure 16 shows the 1st (in blue) and the 2nd (green) driving tests for CO emissions as a function of driving cycle velocity, taking into account the repeatability results described previously.

Analysing the CO emissions of each part of the cycle, the high CO emission observed for Peugeot at WLTC cycle with E5 corresponds to the CO emitted during extra-urban phase of WLTC (Air / Fuel ratio decrease strategies in order to maintain exhaust temperature in high speed / high load conditions), while for NEDC cycle the CO emissions is mostly obtained during the first cycle (EC-195) and can be explained by the delay to the catalyst to be completely effective achieving its working temperature (light-off). The effect of ethanol is clear observed for the Peugeot extra-high phase of WLTC cycle with E25, Figure 17, where the CO emissions are drastically reduced. This results shows that ethanol does not seem to have a significant effect on light-off behaviour and efficiency of the catalyst, but has a positive effect when entering $\lambda<1$ zones of the engine map. As a consequence, ethanol increase can have a very positive impact in real driving conditions.

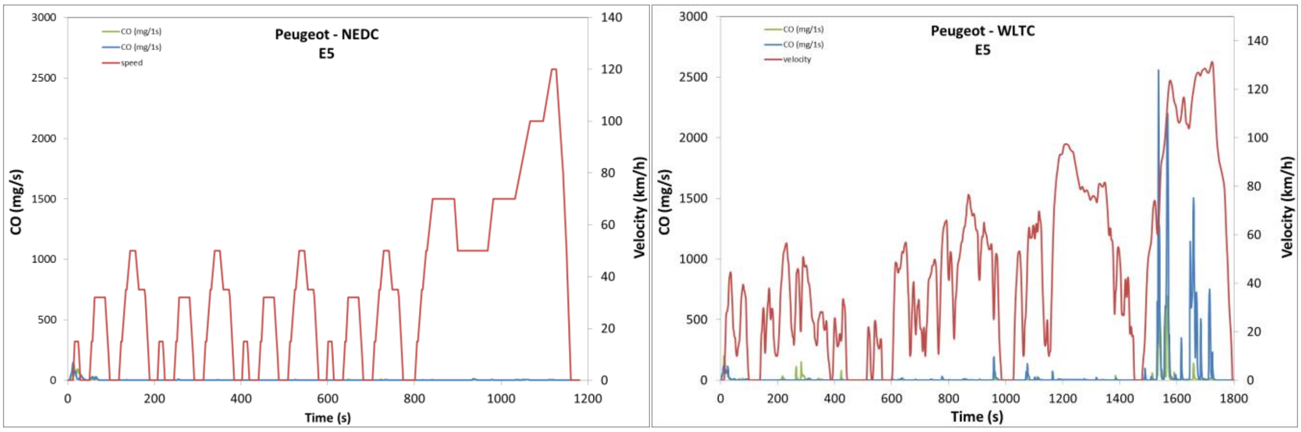


Figure 16. CO emissions (green) 1st driving test and (blue) 2nd driving test of Peugeot 208 with E5 at NEDC and WLTC cycles

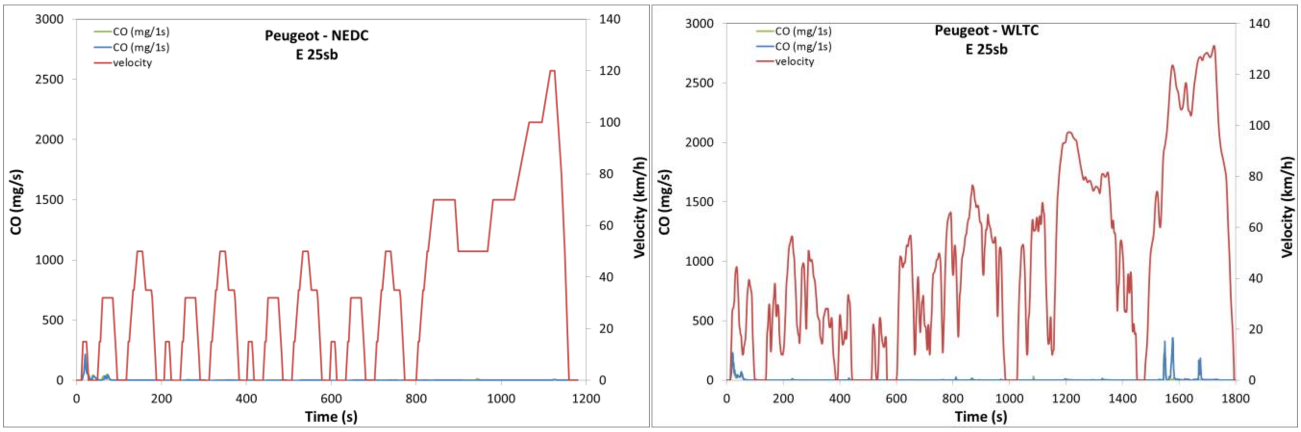


Figure 17. CO emissions (green and blue) of Peugeot 208 with E25sb at NEDC and WLTC cycles

3.1.2 HC emissions

Figure 18 shows the average of HC emissions depending on fuel formulation, E5, E10, E20sb, E20RON95 and E25, for both vehicles and cycles. It is important to notice that all engines and cycles respect Euro 5 and Euro 6 HC limits (0.068g/km). There is no significant impact of engine technology.

Nevertheless, there is a clear cycle effect with emissions of WLTC cycles lower than NEDC ones. In addition, it is observed an effect of ethanol content only for Golf which presents a HC emissions decreasing over both NEDC and WLTC cycles when increasing ethanol content (~ -30% of HC emissions). For Peugeot, HC emissions are relatively constant independent of ethanol (-10% for NEDC cycle and -15% for WLTC cycle).

By analysing each phase of the cycles, Figure 19 and Figure 20, it is observed that for both vehicles, cycles and all fuels in the matrix, HC emissions are important in the beginning of running, EC-195 of NEDC cycles and low phase for WLTC cycle. As before, it can be due to the delay of the catalyst to be effective and the impact on combustion (HC emission level before catalyst light-off). The analysis of real-time HC emissions seems to show that this second hypothesis is the most probable one.

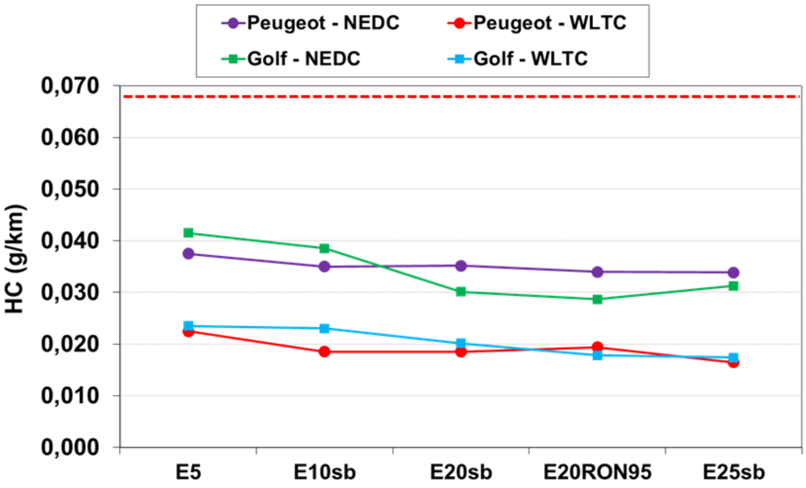


Figure 18. HC emissions in g/km for NEDC and WLTC cycles for Golf and Peugeot depending on ethanol content from E5 to E25sb

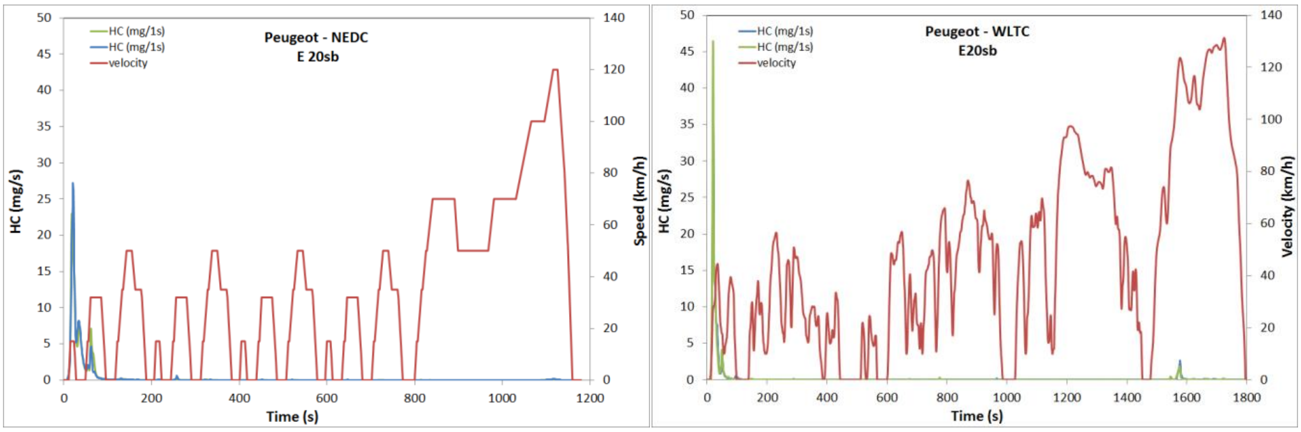


Figure 19. HC emissions (green and blue) of Peugeot 208 with E20sb at NEDC and WLTC cycles

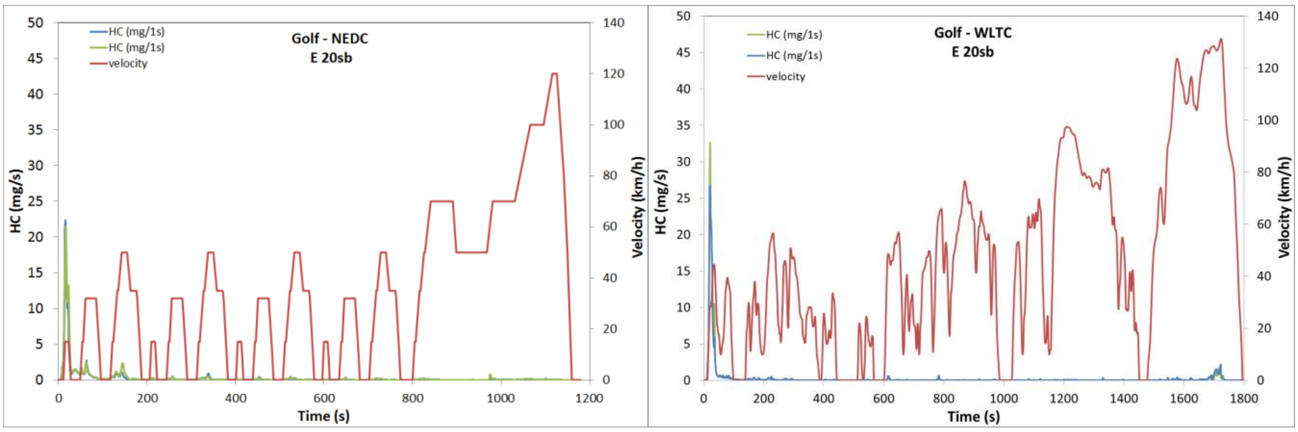


Figure 20. HC emissions (green and blue) of Golf 7 with E20sb at NEDC and WLTC cycles

3.1.3 NO_x emissions

Figure 21 present the average NOx emissions for both cycles, NEDC and WLTC, for both vehicles and all fuels matrix from E5 to E25sb. As for CO and HC emissions, here all fuels, vehicles and cycles respect Euro 5 and Euro 6 NOx emissions limits (0,06g/km).

There is no clear impact of engine technology, for both vehicles NOx emissions slightly increase when adding ethanol on gasoline base. Golf and Peugeot over WLTC cycle presents the most important evolution of NOx around 45% of emissions increase, whereas over NEDC cycle this raise is only around 30%.

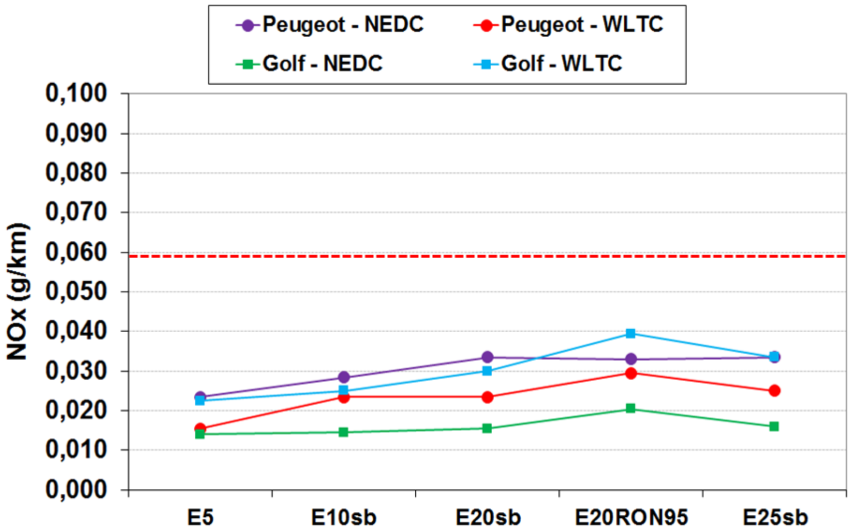


Figure 21. NOx emissions in g/km for NEDC and WLTC cycles for Golf and Peugeot depending on ethanol content from E5 to E25sb

Figure 22 and Figure 23 show an example, with E10 blend, of NOx emitted after each cycle phase for Peugeot and Golf 7 running. As for HC emissions, here, there is a great quantity of NOx emitted in the Low phase for WLTC and EC-195 for NEDC. In addition to it, it is observed a peak of NOx emissions well correlated with acceleration phases, especially for WLTC.

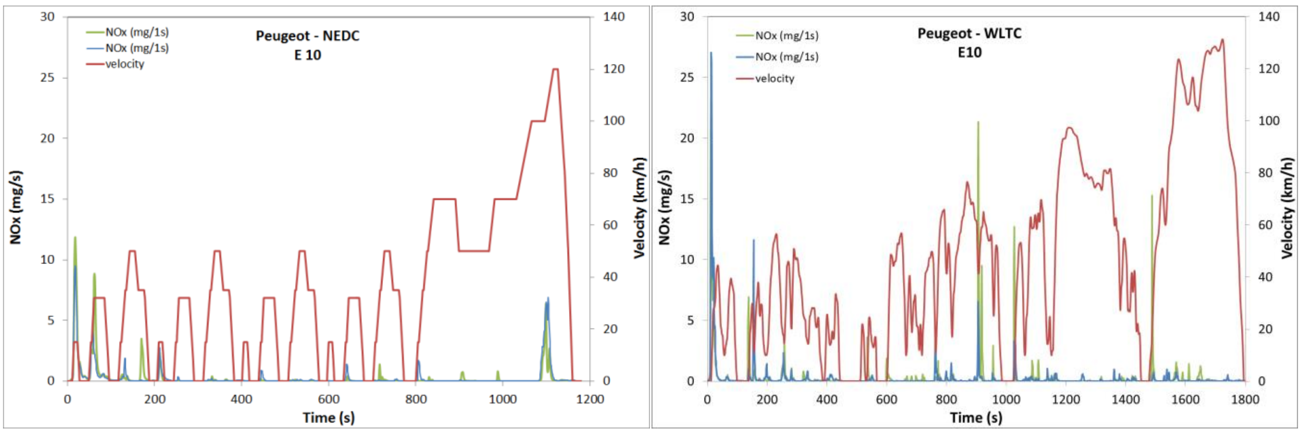


Figure 22. NOx emissions (green and blue) of Peugeot 208 with E10 at NEDC and WLTC cycles

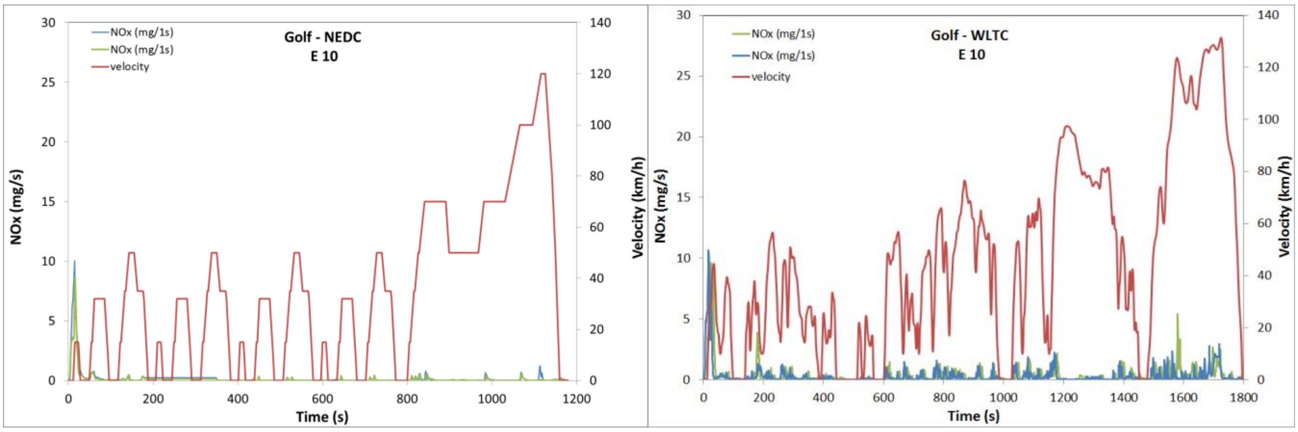


Figure 23. NOx emissions (green and blue) of Golf 7 with E10 at NEDC and WLTC cycles

3.1.4 Particles number and mass

Figure 24 and Figure 25 present the average particles number and mass emissions, respectively, for both cycles, NEDC and WLTC, for both vehicles and all fuels matrix from E5 to E25sb.

For all fuels in the matrix, both vehicles and cycles the emission in terms of particles mass respect Euro 5 and Euro 6 limits (0,0045g/km). Also the tendency observed for NEDC and WLTC is quite similar with particles number /km and mass decreasing according to ethanol content from E5 to E25sb for both vehicles and cycles.

In terms of particles number there is a net impact of engine technology since Golf present higher emissions than Peugeot for both cycles. Also, Golf does not respect Euro 6 standards (6E-11/km) with particles number emissions between 2x1012 for E5 and 8x1011 particles/km for E25sb fuel. For Peugeot, particles number emissions are lower Euro 6 standards and there is no significant difference between NEDC and WLTC cycles, particles/km decreases from E5 to E20sb to further stabilizes from E20sb, E20RON95 and E25sb.

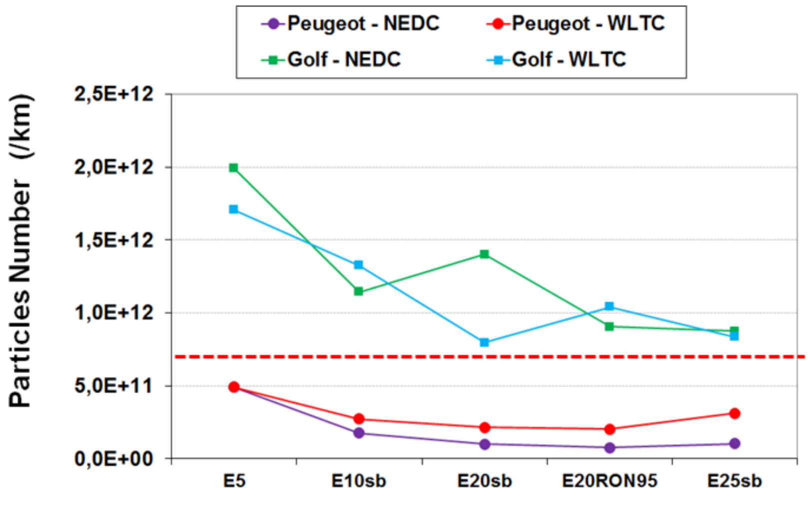


Figure 24. Particles in number/km emissions for NEDC and WLTC cycles for Golf and Peugeot depending on ethanol content from E5 to E25sb

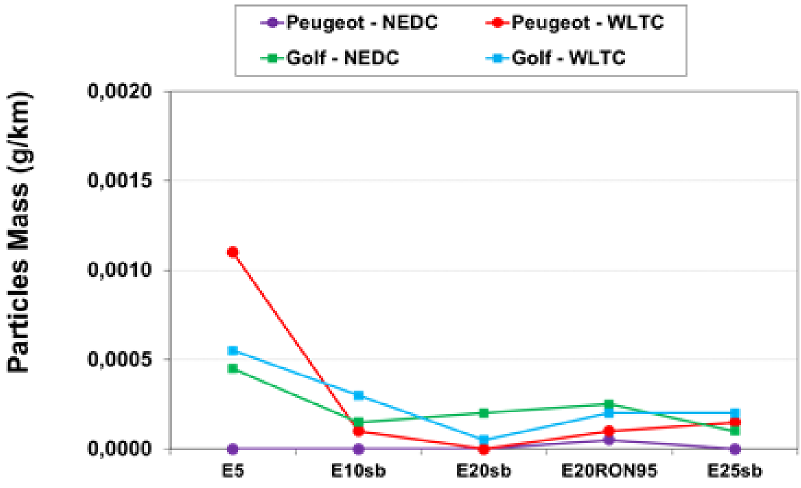


Figure 25. Particle emissions in g/km for NEDC and WLTC cycles for Golf and Peugeot depending on ethanol content from E5 to E25sb

Highlights of regulated emissions:

The main results of tests over two vehicles and two cycles with a fuel matrix from 5% to 25% ethanol volume in gasoline base fuel are:

- ✓ **Golf and Peugeot following NEDC and WLTC cycles respect EURO 5 emission limits with all fuels in the fuel matrix except for CO emissions of Peugeot WLTC cycle for fuels containing less than 20% of ethanol**
- ✓ **Ethanol has a clear positive impact for vehicles which high CO emissions. Indeed, adding ethanol seems to favours the CO emission reduction and has consequently a strong potential for real-life pollutant emissions**
- ✓ **For HC emissions there is no significant impact of ethanol, however there is a clear cycle effect with emissions of NEDC cycles higher than WLTC ones**
- ✓ **Ethanol has a negative effect over NOx emissions which slightly increase with ethanol content improvement. Nevertheless, NOx emissions are extremely low and respect EURO 5 and even EURO 6 limits for both vehicles and cycles with all fuel matrix tests**
- ✓ **Positive effect of ethanol in particles number and mass, especially for direct injection technology.**

3.2 CO_2 emissions and Fuel consumption

3.2.1 CO_2 emissions

Figure 26 present the average of CO2 emissions for both cycles, NEDC and WLTC, for both vehicles and all fuels matrix from E5 to E25sb.

Results shows the differences between both engines: Golf presents higher CO2 levels than Peugeot considering both cycles. Also, Golf presents a quite constant CO2 levels independently of ethanol volume, around 125g/km for WLTC cycle and 130-133g/km for NEDC cycle. In the case of Peugeot, CO2 emissions decrease, especially for NEDC cycle with almost 5% of CO2 reduction, this difference can be attributed to the engines technology.

CO2 emissions are direct linked to H/C ratio of fuels blends. As shown on Table 2, the H/C ratio of our fuel matrix does not present a significant deviation among all fuels, mainly due to the quite high H/C ratio of E10 fuel; this could explain the constant levels of CO2 for Golf and small impact for Peugeot. Moreover, the tested vehicles are standard ones, without any modification and especially without any ethanol detection and optimization strategies that could induce reduction of CO2 emissions.

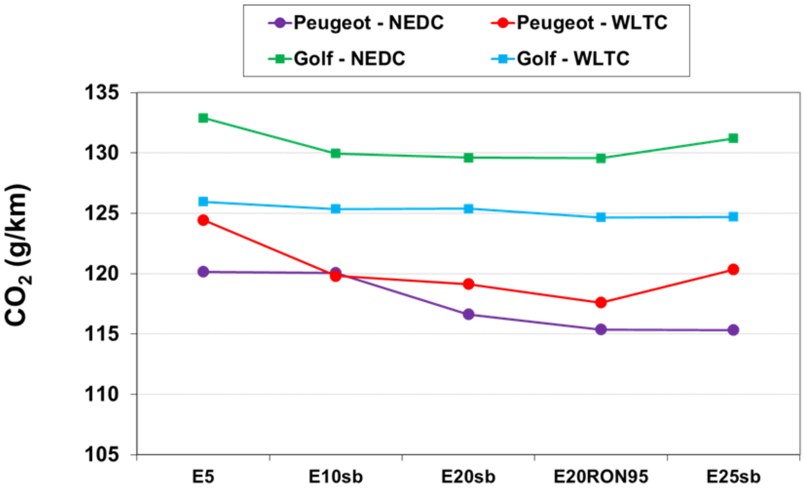


Figure 26. CO_2 emissions in g/km for NEDC and WLTC cycles for Golf and Peugeot depending on ethanol content from E5 to E25sb

3.2.2 Fuel consumption

Figure 27 present the average of Fuel consumption for both cycles, NEDC and WLTC, for both vehicles and all fuels matrix from E5 to E25sb.

As expected the fuel volume consumption increases with ethanol volume going from 5% to 25%, with fuel E20RON95 presenting higher consumption except for Peugeot WLTC. Golf presents higher consumption than Peugeot for both cycles, especially NEDC. The most important increment is when ethanol content goes from 5% to 20%. Higher ethanol volume, 25%, presents no effect on fuel consumption, except for Peugeot WLTC cycle, where it slightly increases.

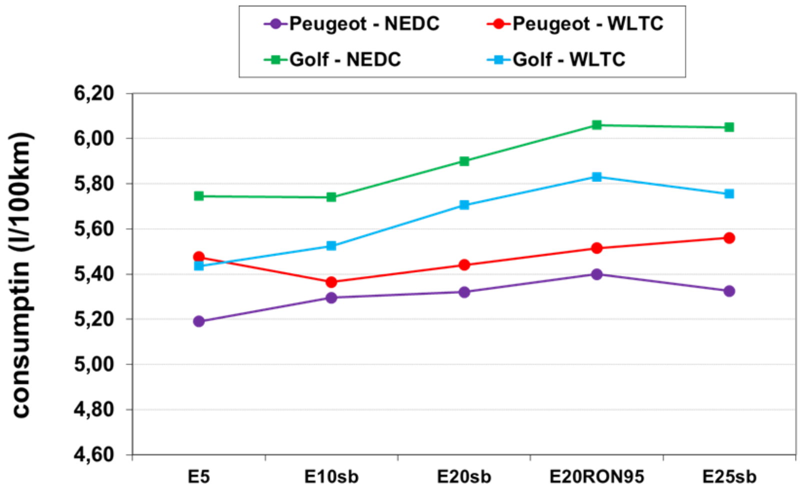


Figure 27. Fuel consumption data for NEDC and WLTC cycles for Golf and Peugeot depending on ethanol content from E5 to E25sb

The theoretical fuel consumption can be calculated by the equation below:

$$Fuel\ Cons._{theo} = Fuel\ Cons._{measured\ \ REF} + Fuel\ Cons._{measured\ \ REF} \times (Energy\ cont._{REF} - Energy\ cont._{fuel})/\ Energy\ cont._{fuel}$$

where, *Fuel cons*$_{.theo}$ corresponds to the theoretical fuel consumption, *Fuel Cons.*$_{measured\ REF}$ is the Fuel consumption measured of the reference fuel, which in our case corresponds to the E10 blend; *Energy cont.*$_{REF}$ is the Net Calorific Value in volume of the reference fuel (E10) and the *Energy cont.*$_{fuel}$ is the Net Calorific Value in volume of the fuel under study.

Figure 28 shows the results of measured and calculated fuel consumption of fuels from the same gasoline base (E10, E20sb and E25sb) for both vehicles and cycles. For Golf, measured and calculated fuel consumption is well correlated for both cycles. However for Peugeot, both cycles, calculated values are higher than measured ones, especially NEDC cycle. This deviation is more important for fuels with high ethanol content (E25, 29855kJ/L of energy content). This effect can be explained by the combustion regulation which is different between indirect and direct injection. In addition, ethanol content plays an important role since it will impact the combustion regulation by changing latent heating vaporization and octane index and so the fuel tendency to auto-ignition.

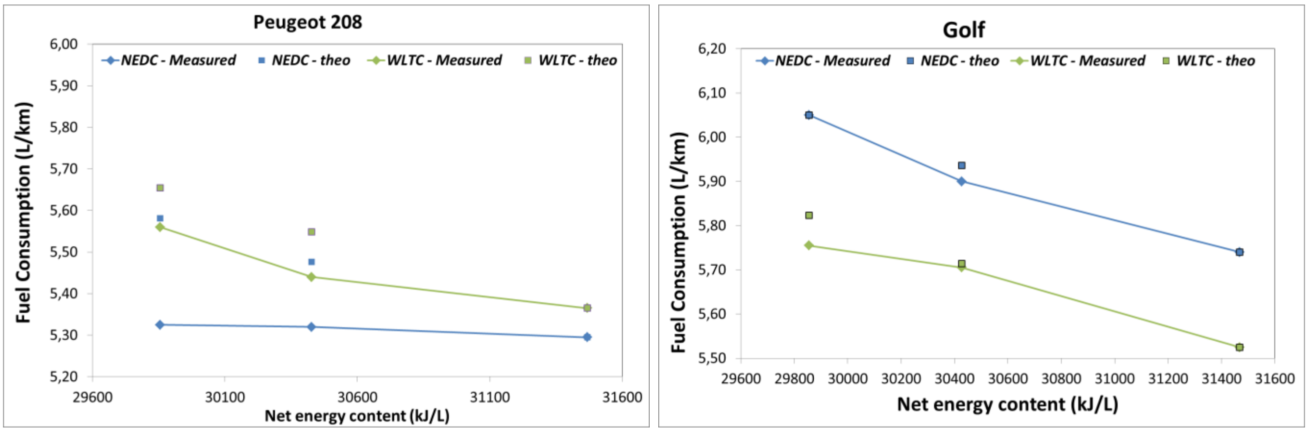


Figure 28. Measured and calculated fuel consumption for Peugeot 208 (left) and Golf (right) both cycles as a function of Energy content of fuels from the same gasoline base (E10, E20sb and E25sb)

Highlights of CO_2 and Fuel consumption:

The main results of tests over two vehicles and two cycles with a fuel matrix from 5% to 25% ethanol volume in gasoline base fuel are:

- ✓ **CO_2 emissions are direct related to H/C ratio**
- ✓ **Fuel consumption in volume raises with ethanol content**
- ✓ **Fuel consumption is clearly reduced with fuel blends containing high Net Calorific values in volume, especially for WLTC cycle**

3.3 Non-regulated pollutants emissions

3.3.1 Benzene

Figure 29 shows the impact of ethanol on the average of benzene emissions in mg/km. It is observed a positive impact of ethanol on benzene with reduction of emissions from E5 to 25sb for both vehicles and cycles. For Peugeot NEDC cycle, fuel E20sb present a slightly decrease of benzene emission from E5 to E10, higher ethanol quantities seems to do not have an important impact, indeed benzene emissions are quite constant from E10 to E20RON95 and E25sb. Fuel E20sb present a very low benzene emissions value with Peugeot during NEDC cycle, the control test does not indicate any apparatus problem or measurement deviation. Other parameters seem to play a role for this fuel blend which investigation is beyond the scopes of the present work.

Figure 30-left shows the impact of benzene content of fuel blends over benzene exhaust gas emissions and Figure 30-right, the impact depending on aromatics content. It is observed that E25sb, which contains higher aromatics and benzene content than fuel E20RON95, present almost the same benzene emissions as the later. Among fuels with the same gasoline base (E25sb, E20sb and E10) by decreasing ethanol content, the benzene emissions increase. Thus, higher ethanol content seems to favours the reduction of benzene emissions at exhaust gases which is due to a dilution effect.

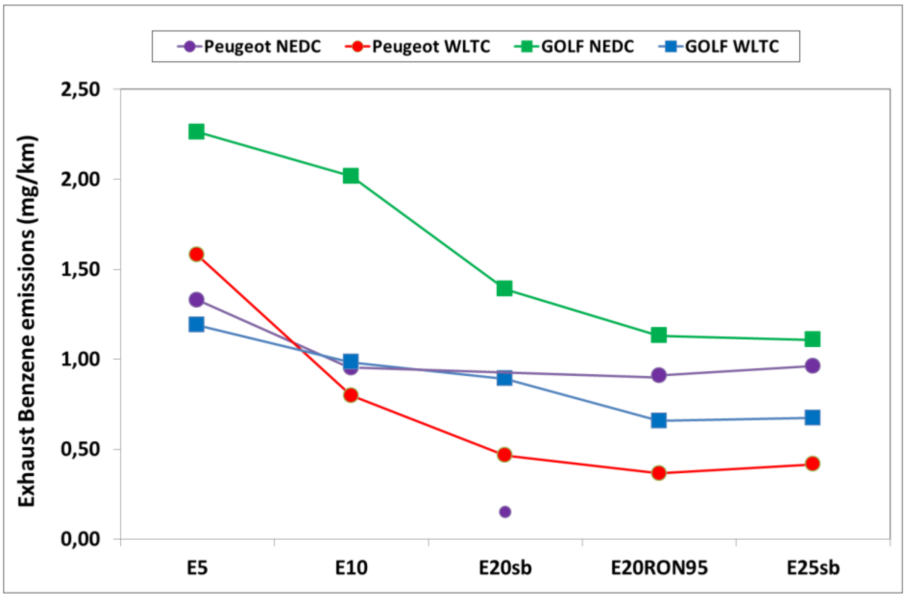


Figure 29. Benzene emissions for NEDC and WLTC cycles for Golf and Peugeot depending on ethanol content from E5 to E25sb

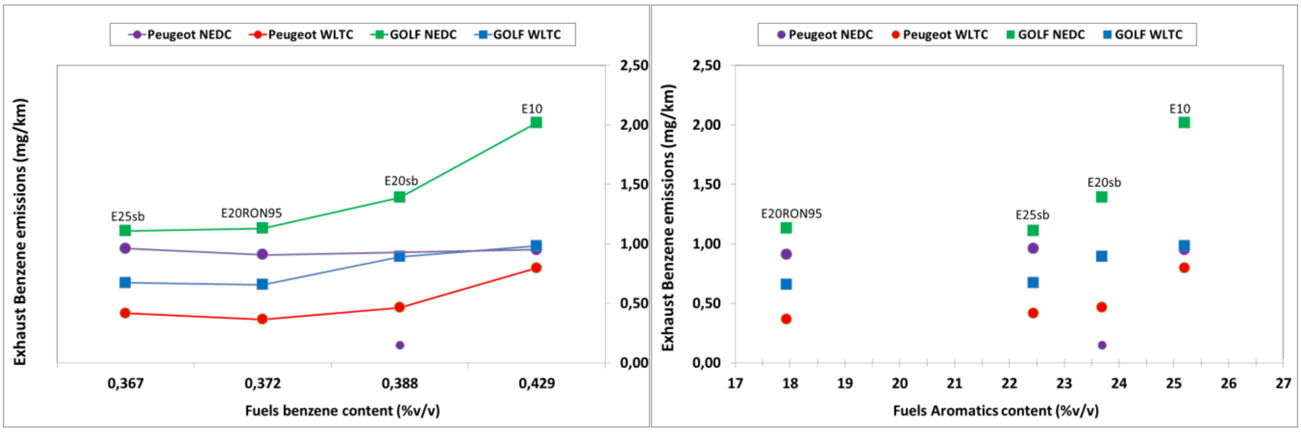


Figure 30. Impact of benzene content (left) and aromatics content (right) of fuels over benzene exhaust emissions

4 Conclusion

The present work aimed to answer measure the pollutant emissions, regulated and non-regulated as well as fuel consumption when running with different ethanolated fuels. The work was carried out around the test of 2 vehicles, Peugeot 208 and Golf 7, on NEDC and WLTC cycles, with standard pollutant emissions measurements, but also unregulated pollutant emissions.

Five fuels were used to the fuel matrix from 5%v/v of ethanol to 25%v/v of ethanol volume in gasoline bases. The main results have shown that all fuels respect the EN 228 standard, even the splash blended fuels (E20sb and E25sb).

For both cycles and vehicles the EURO 5 standard is respected except for CO emissions of Peugeot WLTC cycle for fuels containing less than 20% of ethanol. Ethanol had a positive impact for vehicles which high CO emissions. Indeed, adding ethanol seems to favours the CO emission reduction. This is also the case for particles number and particles mass where a positive impact of ethanol was observed in order to reduce particles emissions.

For HC, there is a slight decrease of emissions when adding ethanol. On the other hand there is a clear cycle effect with emissions of NEDC cycles higher than WLTC ones.

In the case of NOx, ethanol seems to have a negative effect since it slightly increase when higher ethanol volumes are used. Nevertheless, NOx emissions respect EURO 5 and EURO 6 standards for both vehicles and cycles with all fuel matrix tests.

CO2 emissions are quite constant for Golf 7 and present only a limited impact for Peugeot which can be explained by the H/C ratio of fuels matrix that does not present a significant different among them.

As expected, fuel consumption raises when net calorific values decrease.

To summarize roughly the positive and negative points of fuels E20sb, E20RON95 and E25sb taking E10 as reference fuel, one can build the table below where the green point represent the positive impact of the parameter, the red points corresponds to negative impact and the yellow marks corresponds to very similar/equal impact of the property in comparison to the reference fuel E10.

Table 11.Positive (green), negative (red) and similar (yellow) points of fuels E20sb, E20RON95 and E25sb in comparison to the reference fuel E10.

	E20sb	**E20RON95**	**E25sb**
EN228 limits			
RON			
Energy content			
CO (g/km)			
HC (g/km)			
NOx (g/km)			
Fuel cons. (L/km)			
CO2 (g/km)			
Particles (g/km)			
Particles (#/km)			

In general, E20sb fuel present more advantages than E20RON95 and E25sb fuels with only one real disadvantage, HC emission, but better performances in terms of NOx and Particulates as well as RON and energy content. The better RON and Energy content has a real positive effect lowering volumetric fuel consumption in comparison to E20RON95 and E25sb.

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