Emissions from Power-to-liquid fuels – IFPEN for T&E

Summary report – December 2021

I. Purpose of the document

The aim of the project present work is to respond to the T&E's call for tender, by measuring on a spark ignited (petrol) vehicle the pollutant emissions (regulated and non-regulated) and fuel consumption when running with different fuels representative of future e-fuel gasoline blends. The work was carried out with **1 recent (Euro 6d-temp) vehicle**, a Mercedes A Class, on WLTC and RDE drive cycles performed on a chassis dyno, measuring **standard regulated pollutant emissions as well as CO_2, sub-23nm particles, aldehydes, N_2O, and NH_3 emissions**.

The fuel matrix includes four fuels with different blending strategies: (1) an E10 homologation grade fuel (RON 98) as a reference; (2) a zero aromatic blend with a high RON value (RON 102); (3) a low aromatics blend (RON 104); (4) a blend including the zero aromatic reference as gasoline base in mixture with ethanol which can obtained through advanced production pathways (2G). The results have shown that all formulated fuels are within most of the EN228 boundaries. The volatility and distillation properties are the ones that exceed E228 limits, nevertheless the fuels are still compatible with existing vehicles. It should be highlighted that an aromatic content decrease is likely to correspond to a more volatile fuel which is consistent with the proposed matrix.

Note to the reader: Glossary available at the end of the report.

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II. Executive summary

Compliance with emission standard

With no exception, this experimental campaign shows that the vehicle complies with the normative thresholds. It is worth noting the **3.6% gain in consumption** (WLTC cycle) for fuel1 and fuel2 (without ethanol). This result is largely related to the fuel properties. Non-oxygenated fuels have a higher net calorific value in volume than oxygenated fuels, which implies that for the same energy demand from the vehicle, the fuel consumption by volume will decrease. Following the trend observed for fuel consumption, a gain of **3.6% on CO_2 emissions** (WLTC cycle) is observed. Finally, it should be emphasized that a gain of more than **90% on PN_{23} emissions** (WLTC cycle) is observed certainly due to the low aromatic content.

Impact of Non-Regulated Pollutants (NRP)

For the N_2O and formaldehyde, this campaign establishes that emissions are low and constant for all fuels given the uncertainty regardless of the cycle. Regarding NH_3, no clear trend is observed on WLTC cycle, while on RDE cycle, fuel2 and fuel3 contribute to higher emissions than E10 and fuel1. In the case of acetaldehyde emissions, despite low emissions, E10 and fuel3 (containing 10%v/v of ethanol) seem to be responsible of higher emissions than the other fuels. Similarly, to regulated PN_{23} emissions, a decrease of more than 90% on PN_{10} emissions (WLTC) is also observed.

Significant difference between tailpipe and engine out emissions

With a few exceptions, this experimental campaign shows that emissions trends witnessed at engine out are also valid at tailpipe. The exception is CO emissions where the difference between the fuels is less pronounced from engine emissions out. A slight increase is observed with alternative fuels which may be related to unoptimized engine calibration. Regarding PN_{10} emissions, GPF allows a reduction by one to two orders of magnitude regardless of the cycle. The fuel impact remains visible for tailpipe emissions with an order of magnitude less of PN_{10} for alternative fuels compared to E10.

Increase in urban use

Emissions levels are significantly higher in urban use whatever the fuel is, especially aldehydes and N_2O emissions:

- 3 to 5 times higher for formaldehyde considering the standard urban WLTC phases compared to full WLTC type driving. Regarding acetaldehyde emissions, fuels with ethanol seem to emit more in the urban phase compared to full WLTC cycle (2 to 4 times higher).

- 5 times higher for N_2O considering the standard urban WLTC phases compared to full WLTC type driving.

These emission levels are even higher by focusing on conditions more representative of urban use (very short and slow journeys).

The overall emissions comparison between E10 and e-gasoline surrogates shows:

- **3.6 % lower fuel consumption for fuel1 and fuel2** (-0.28L / 100km), **resulting in 3.5% lower CO_2 emissions (WLTC) and 2.9% lower CO_2 emissions (RDE)**.

- Similar fuel consumption regardless of the cycle for fuel3, while a gain of 3.7% (WLTC) and 2.4% (RDE) is observed on CO_2 emissions.

- Average PN_{23} emission level for e-gasoline surrogates decreased down to $1.1*10^9$ #/km, 97% less than E10 fuel in this study on the WLTC test, a reduction of 87% was witnessed on the RDE test cycle.

- HC emissions of 12 mg/km for e-fuel gasoline surrogates compared to 17 mg/km for E10 fuel on WLTC cycle. Emissions are lower on the RDE cycle and the difference between fuels is not discernible. As a reminder, the limit of the Euro 6 standard is 100 mg/km of *HC* for gasoline vehicles.

- CO emissions of 176 mg/km against 70 mg/km for E10 fuel on WLTC cycle; as a reminder, the *CO* limit of the Euro 6 standard is 1000 mg/km for gasoline vehicles. **It should be noted that this increasing trend is not observed on the RDE cycle.**

- NH_3 emissions are low, no clear trend is observed on WLTC cycle while on RDE cycle, **fuel2 and fuel3 contribute to higher emissions than E10 and fuel1 (two times higher).**

- Aldehydes emissions are not significant for all fuels regardless of the cycle given the minimum detectable concentration (MDC ≤ 2.5 ppm). Emissions mainly occur in the cold-start phase, within the first few minutes of the cycle. Over the rest of cycle, emissions are below the apparatus detection limit. It should be noted that e-fuel gasoline surrogates contribute to decrease the cold phase emissions compared to E10 fuel.

III. Introduction

Production of renewable e-fuels also named power to X fuels, is based on three main inputs: (1) renewable energy from solar plants or wind turbines for example; (2) hydrogen, preferably produced from water electrolysis with the required energy being produced by renewable sources; (3) carbon dioxide, preferably obtained from direct air capture. Non-renewable e-fuels could also be produced if electricity from non-renewable sources. While the technology must face quite a few challenges to reach the industrial scale with a reasonable cost, this approach is under development by several industry stakeholders and several pilot plants are announced worldwide, leading to different chemicals and different fuels.

These e-fuels may be used on their own, however it is really challenging to estimate volume of e-fuels available on the market by 2030. We assume that there will not be enough e-fuels to decarbonize the transport sector and that blends with other existing fuel component such as ethanol may be considered to increase availability. Ethanol is already available at large scale and being more and more produced through advanced processes. Ethanol is accepted up to 20% vol by most modern spark ignition engines with no necessary modification. E85 conversion kits are also becoming quite popular and different car manufacturers are increasing their native flex fuel vehicle models offer in 2021 (Ford, Jaguar, Land Rover). Ethanol's physical and thermal properties are quite interesting for gasoline application. Its composition grants it lower CO_2 emissions, and its high-octane rating allows for higher combustion efficiency and performance. These characteristics have popularized the use of ethanol in recent years. Indeed, as a well-established conventional bio gasoline component (half the countries of the European Union propose E10, and a quarter propose E10 in almost 100% of gas stations[1]), ethanol is a non-negligible fuel fraction today and may be blended with future e-fuels. Produced mainly from conventional (first generation) feedstocks, corn, wheat and sugar beet, its widespread use and potential could foster the development of advanced (second generation) bioethanol production paths using lignocellulosic biomass or different organic residues.

Internal combustion engines may not evolve significantly in the coming years or decade due to limited investments. However, e-fuels are considered by some as a pathway for decarbonising the internal combustion engine for new vehicles or the existing fleet. It is therefore important to assess how these products behave in terms of tailpipe emissions and how they compare to standard fossil fuels.

The aim of the present work is to respond to the T&E’s call for tender, by assessing the impact of e-fuels, that could be available by 2030 on both regulated and unregulated vehicle emissions.

The testing was performed on a roller test bench, both with WLTC and RDE protocols. The work was carried out on a Mercedes A-Class, with engine out and tailpipe measurements of standard pollutant emissions and selected non-regulated products.

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[1] https://www.epure.org/about-ethanol/fuel-market/fuel-blends/

IV. Operating conditions

Fuel matrix

The fuel matrix aims to evaluate fuels that may be representative of future e-fuel gasoline blends. It covers products that are likely to be found in the future in the EU market.

By 2030, gasoline fuel production and use will certainly be facing many challenges from:

- the constrains of using renewable sources from the European directive RED II and its updates.
- the large availability of certain fuel paths or the lower technology readiness level of others.
- the usage competition for renewable products especially with aeronautics.
- the fuel specifications which are highly related to type of vehicles available.

The development of e-fuel products for road transport should consider all these parameters.

In addition, it should be emphasized that the fuel impact on engine performances and emissions is a key concern today.

Nowadays, one of the drawbacks of gasoline composition regarding emissions is the aromatic content. The aromatics are used today to reach a certain level of octane, but their content may decrease over the next decade to reduce particulate matter emissions. The direct link between fuel aromatic content and particulate matter emissions is clearly established in the literature.

Regarding the e-fuel process today as described in the scientific literature, the most accepted definition is related to the use a renewable source of electricity to produce a syngas from carbon dioxide and water electrolysis. The resulting H_2/CO mixture is then combined with a Fischer-Tropsch (FT) catalytic process which can produce many chemicals, including the building blocks of a gasoline fuel. The most common catalytic FT processes are related to the use of iron or cobalt catalysts. The first one is probably the most suitable for producing paraffinic components that may contribute to the gasoline pool. The use of Cobalt is, however, preferred today within the FT process.

Potential e-fuel pathways today for gasoline application include Methanol-to-Gasoline process and FT process. These may enable to produce a wide range of products including olefines and iso-paraffinic fuels, but they will probably not be directly compatible with gasoline applications due to the low octane number. Different strategies may be associated to produce more relevant products, and this includes catalytic reforming to produce cyclo-paraffins and aromatics with better RON or oligomerization followed by hydrogenation which may enable the production of different olefins and later iso-alkanes.

It is impossible today to establish exactly what an e-fuel gasoline formulation will be within the next decade. However, based on current knowledge and different technological constraints may contribute to favor the production of certain blends. First, future e-fuels may have to comply with the current gasoline specification to allow existing fleet compatibility. Then, since the engine architecture will probably be frozen, combustion improvement may have to be originate from the fuel. This implies that improved efficiency and emissions reduction must be considered. Finally, production capacity may be limited first which implies that blends with existing advanced fuels such as ethanol may be considered.

In this context, the current work focuses on a fuel matrix relying mostly on paraffinic fuels with limited aromatic concentration and advanced bioethanol (2G). These components may be representative of an ideal e-fuel formulation meeting all constraints cited above and leading both to an increase in octane rating and a decrease in particulate emissions driven mainly by the aromatic content of the fuel.

The following fuel matrix (Table 1) is used:

- 1 homologation grade fuel compliant with EN228 standard:
    - E10: this reference fuel follows the European regulation EU REGULATION 2008/692/EC (Annex IX) which defines the quality of the fuels used during the homologation cycles.
- 3 gasoline fuels potentially representative of physical and chemical properties of future E-gasoline blends in the EU market:
    - E-fuel gasoline surrogate "Zero aromatic" – fuel 1
    - E-fuel gasoline surrogate "Low aromatics" – fuel 2
    - E-fuel gasoline surrogate "Zero aromatic" in mixture with advanced bioethanol (2G) – fuel 3

Fuel 1 and fuel 2 aim to evaluate the impact of a certain fuel variability for the octane number and the aromatic content. It should be noted that today's lack of industrial or even representative pilot units for e-fuels makes it difficult to supply such products. The three e-fuel gasoline blends have therefore been developed from non-renewable sources through a 'blending model' approach, using the following model solvents: a mixture of light aromatics (< C_8) and C_5-C_8 hydrocarbons including linear, branched alkane such as isopentane, isooctane and alkene such as diisobutylene. These blends may of course not be the e-petrol blends that reach the market in 2030. However, based on the current knowledge of the technology and the engine compatibility constraints placed on the fuel) they are a reasonable assumption on what the e-petrol formulation in the future could be. The fuel was blended with the following aims:

- A moderate to high fuel sensitivity (RON-MON difference) to prevent engine knock.
- Specifications of the identified fuel blends approaching the current EN228 specifications to ensure existing fleet capability.

It should be emphasized that the followed approach may lead to ideal formulations. Indeed, combination of processes may deteriorate to a certain extent the fuel performance compared to the results presented here as these processes will not aim at developing solvents but probably complex blends.

Table 1. Fuel matrix

Notation	Formulation	Standard
E10	Homologation grade fuel (10%v/v of ethanol and RON of 98)	EN228
Fuel1	Zero aromatic (RON 102)	
Fuel2	Low aromatics (RON 104)	
Fuel3	Blend with Fuel1 as base fuel + 10%v/v of ethanol	

Fuel1 and fuel2 do not have the same gasoline base.

Fuels properties

Table 2 shows the detailed analysis of the studied fuels. EN228 specifications have been considered as the target for the fuel blends. However, some deviations have been obtained with the current fuel matrix regarding the volatility and the distillation. Indeed, the DVPE, E70 and E100 are exceeding EN228 limits. It should be highlighted that if we assume that aromatic content decreases by 2030, then more volatile fuels are likely to be obtained, which is therefore consistent with the proposed matrix. A more volatile fuel may also improve the fuel/air homogenization and thus the combustion process.

Table 2. Detailed properties analysis of fuels matrix

	Unit	Limit (EN228)*		Method	Results			
		Min	Max		E10	Fuel1	Fuel2	Fuel3
Copper strip corrosion (3h, 50°C)	Rating	Class 1		EN ISO 2160	1b	1	1	1
Oxidation stability	Minutes	360		EN ISO 7536	>480	>960	>960	>960
Existent gum content (solvent washed)	mg/100mL		5	EN ISO 6246	<1	<0.5	<0.5	<0.5
Existent gum content					6	0.5	0.5	0.5
PHYSICAL PROPERTIES								
Density @ 15°C	kg/m^3	720	775	EN ISO 3675	748.4	763.3	726.0	741.0
DVPE @ 37.8 °C	kPa	45 summer 60 winter	60 summer 90 winter	EN ISO 13016-1	56.4	55.2	60.9	66.2
DISTILLATION								
IBP	°C			EN ISO 3405	35.0	49.7	39.8	44.8
5%Vol	°C				50.9	53.6	49.9	47.3
10%Vol	°C				55.1	54.1	52.6	48.0
20%Vol	°C				60.2	55.1	55.3	49.1
30%Vol	°C				64.8	56.4	58.6	50.3
40%Vol	°C				70.0	57.8	62.9	51.7
50%Vol	°C				94.1	60.0	69.3	53.4
60%Vol	°C				102.6	63.7	78.4	56.8
70%Vol	°C				107.5	70.5	90.3	66.5
80%Vol	°C				114.1	85.7	98.7	80.6
90%Vol	°C				134.2	99.3	101.1	98.5
95%Vol	°C				160.4	100.5	102.2	100.1
FBP	°C		210		176.6	106.0	107.3	106.5
Residue	%Vol		2		1.0	1.0	0.9	0.9
E 70°C	%Vol	22 summer 24 winter	50 summer 52 winter		40.0	69.5	50.9	73.1
E 100°C	%Vol	46	72		56.1	92.9	82.8	93.4
E 150°C	%Vol	75			92.9	>99.0	>99.0	>99.0
COMPOSITION								
Ethanol	%Vol		10	EN ISO 22854	9.3	<0.1	<0.1	9.9
Olefins	%Vol		18		6.8	17.0	17.0	13.9
Aromatics	%Vol		35		26.0	<0.1	10.0	<0.1
Benzene	%Vol		1		<0.1	<0.1	<0.1	<0.1
OCTANE INDEX								
RON	Index	95		EN ISO 5164	97.1	102.3	104	104
MON	Index	85		EN ISO 5163	86.3	87.3	89.3	88.0
COMBUSTION								
Net calorific value in mass	MJ/kg			ASTM D 240-Calculated	41.36	42.80	42.77	40.00
O/C	v/v			Calculated	0.032	-	-	0.051
H/C	v/v				1.937	2.036	2.030	2.135

** The limits considered in France correspond to the Summer grade (Class A of EN228)*

Vehicle tests: operating conditions

The impact of e-fuels on regulated and non-regulated pollutants emissions during RDE and WLTC driving cycles were measured on a Mercedes A Class, sourced by IFPEN. Its main technical data and emissions limits obtained from the certificate of conformity are described in the Table below. The vehicle is homologated according to EURO 6d-temp standard; it has recent engine technology and a turbo charger is present. The vehicle is also equipped with a 3-way catalyst and a gasoline particle filter (GPF).

Table 3. Vehicle's technical characteristics[2]

Brand	Mercedes
Registration date	24/10/2019
Kilometers (before tests)	16 919 km
Category	A Class
Serie	180 136ch Style Line
Empty weigh (kg)	1 350
ENGINE	
Max power kW (ch)	100 (136)
Engine zine (cm3)	1 332
Cylinder	4
Max torque (Nm)	200
Injection type	Gasoline direct injection (GDI)
Supercharger	Yes
Polluting level	Euro 6
CONSUMPTION	
Combined (L/100km)	5.2
CO_2 emissions (g/km)	119
POLLUTANTS EMISSIONS	
CO (mg/km)	111.0
HC (mg/km	23.2
NOx (mg/km	26.8
PM (mg/km)	0.24
PN (#/km)	1.09×10^{11}

Experimental set-up and facilities

The roller bench n° 107 at IFPEN was used for the present work (Table 4). The roller bench is located into a conditioned chamber maintained at 23°C ± 3°C. The driver was assisted by a driver aid system to follow driving cycles. Roller rotation speed is controlled electronically. The exhaust gases emission was collected and measured according to the Constant Volume System (CVS) based on a full flow dilution tunnel. Figure 1 and Figure 2 show the scheme of roller bench n° 107 and the analytical combined apparatus.

Table 4. Roller bench technical characteristics

Power (kW)	55
Speed (km/h)	160
Type	Bi roller
Ventilation maximum speed	120 km/h
Temperature	23 °C ± 3 °C
Hygrometry	45 % ± 10 %

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[2] References: Mercedes Certificate of Conformity; https://www.largus.fr/

Figure 1. Scheme of roller bench n°107

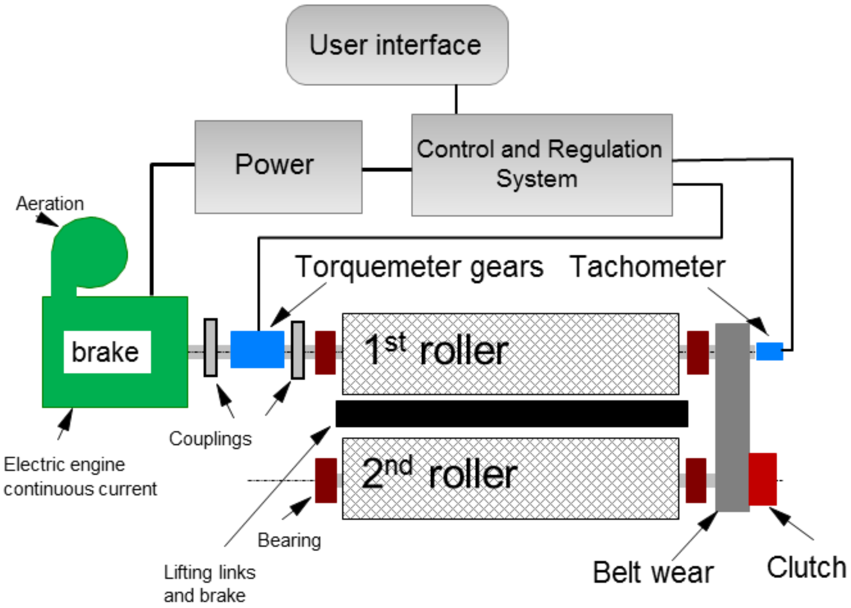
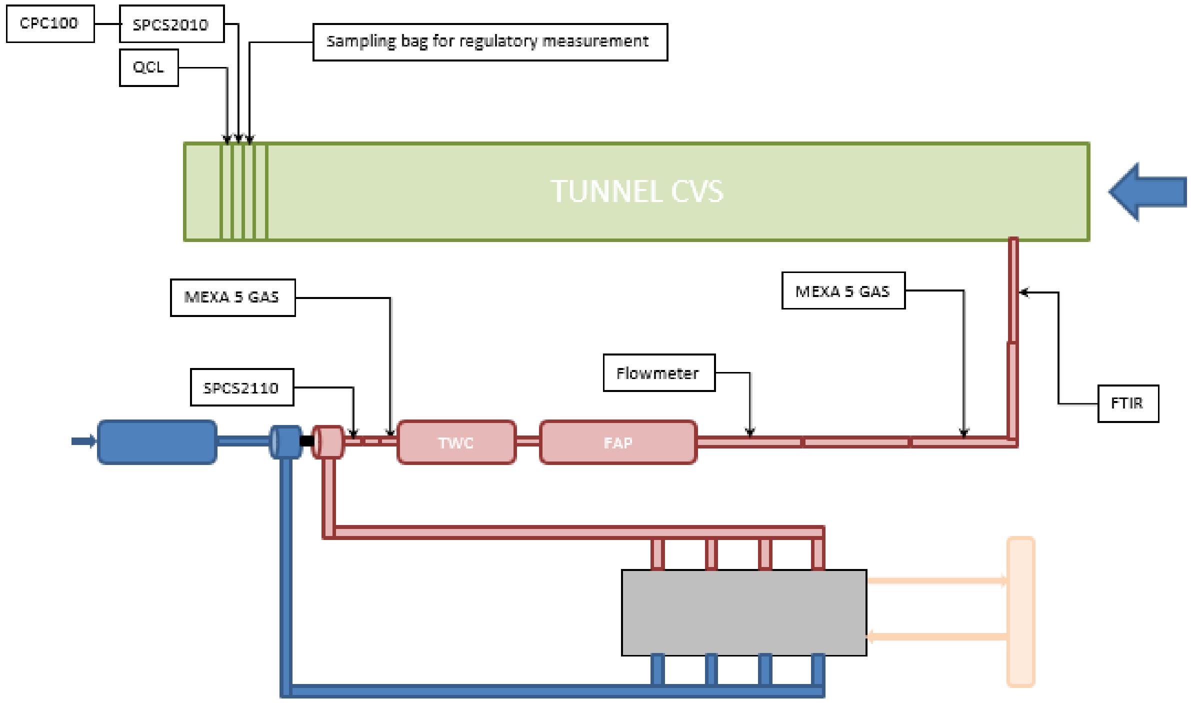


Figure 2. Illustration of the engine out and tailpipe emission measurements targeted



The gaseous emissions were collected using Tedlar® bags and further analyzed in terms of regulated and non-regulated pollutant 1hz emissions. Fuel consumption was monitored as well. The different analyzers and the targeted components are provided below (Table 5) for both the regulated and the unregulated emissions.

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

Area	Targeted component	Measure
Tailpipe (raw and CVS diluted)	CO_2	CVS – MEXA Infrared
	CO	CVS – MEXA Infrared
	NOx	CVS – MEXA (chemiluminescence)
	NO	CVS – MEXA (chemiluminescence)
	NO_2	CVS – MEXA (chemiluminescence)
	HC	CVS – MEXA FID
	CH_4	CVS – MEXA FID
	N_2O	CVS – QCL
	NH_3	CVS – QCL
	PN_{23}	CPC 100 (23 nm)
	PN_{10}	SPCS 2010
	PM	Weighting on filter (standard)
	Formaldehyde and acetaldehyde as well as selected HCs	FTIR
Engine out	CO	Raw sample - MEXA
	NOx	Raw sample - MEXA
	HC	Raw sample - MEXA
	PN_{10}	SPCS 2110
	+ additional measurements included: CO_2, NO, NO_2, CH_4, NMHC	-

Standard and well-established analyzers used on chassis dynamometer tests for the characterization of regulated pollutants were used. A diluted gas analysis bay “MEXA 5 GAS” was selected for the characterization of THC, CH_4, CO, CO_2, and NOx emissions. This bay was duplicated to obtain both the tailpipe and engine out emissions. CO_2, NO/NO_2 ratio, CO, HC, PM and PN have also been included. A Gravimetric sampling system (Pallflex filter) was used for determining the particulate matter (PM) emitted. The particles number (PN), with a diameter greater than 10nm, were measured with a SPCS. An additional particle counter CPC 100, located at tailpipe, was implemented for counting particles greater than 23nm, so that simultaneous counting of particles above 10nm and above 23nm is possible.

The measurement of NO, NO_2, N_2O and NH_3 were performed with a Horiba MEXA-ONE-QL-NX bay.

The tailpipe emissions were also characterized by an FTIR (see Appendix 1 – Characteristics of the FTIR). The device enables to measure aldehydes (formaldehyde and acetaldehyde) as well as selected hydrocarbons.

Vehicle test protocol

The first step was to purge the fuel system. Consequently, ahead of testing with each new fuel, the following protocol was performed:

- The vehicle fuel tank was completely drained.
- 5 liters of the new fuel was added, and the vehicle was runned at idle for at least 10 minutes to flush the old fuel from the entire fuel system.
- The tank was drained again and then filled with the new fuel ready to test.
- The vehicle was then preconditioned by running a WLTC cycle.

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

- vehicle entrance and set-up in the roller bench according to the standard conditions
- driving test according to WLTC or RDE cycle
- vehicle soaking during 12 hours with a temperature at 23 ± 3°C
- driving test according to WLTC or RDE cycle

The tests were all repeated twice (two chassis dynamometer runs per vehicle and per operating condition). Each day, a “cold” WLTC (after soaking) was performed followed by a “hot” RDE. Between WLTC and RDE tests, about 4 hours passed.

Soaking	Cold WLTC #1	Soaking	Cold WLTC #2
	Hot RDE #1		Hot RDE #2

A repeatability criterion was defined using CO_2 emissions as the main parameter. Calculation is based on CO_2 measurement over two tests according to the following formula:

$$Repeatability = \frac{2 \times \sigma_{CO2}}{Average \times \sqrt{Nb\_tests}}$$

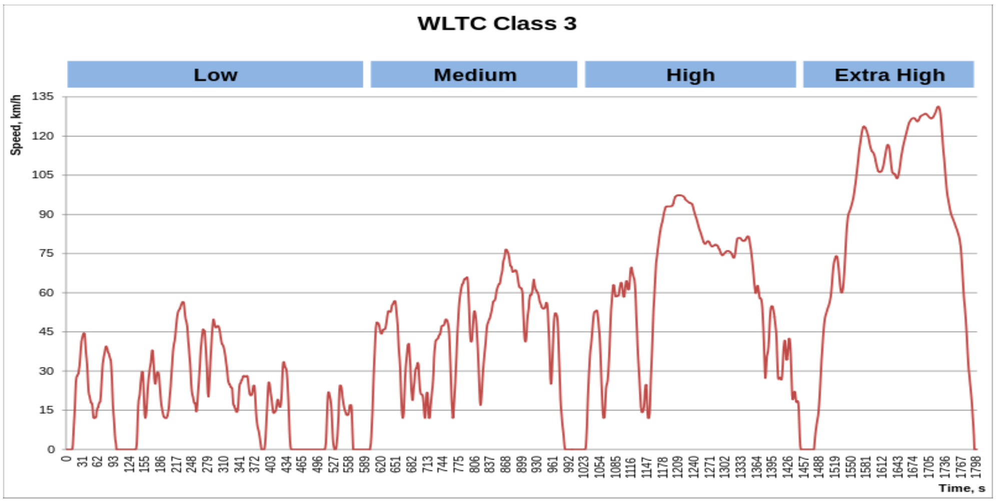
Where Nb_tests is the number of repetitions per test (Nb_test = 2) and σ_{CO2} is the standard deviation of CO_2 global measurements and a validation limit of 1% maximum deviation was imposed.

Test cycles

The protocol included two tests:

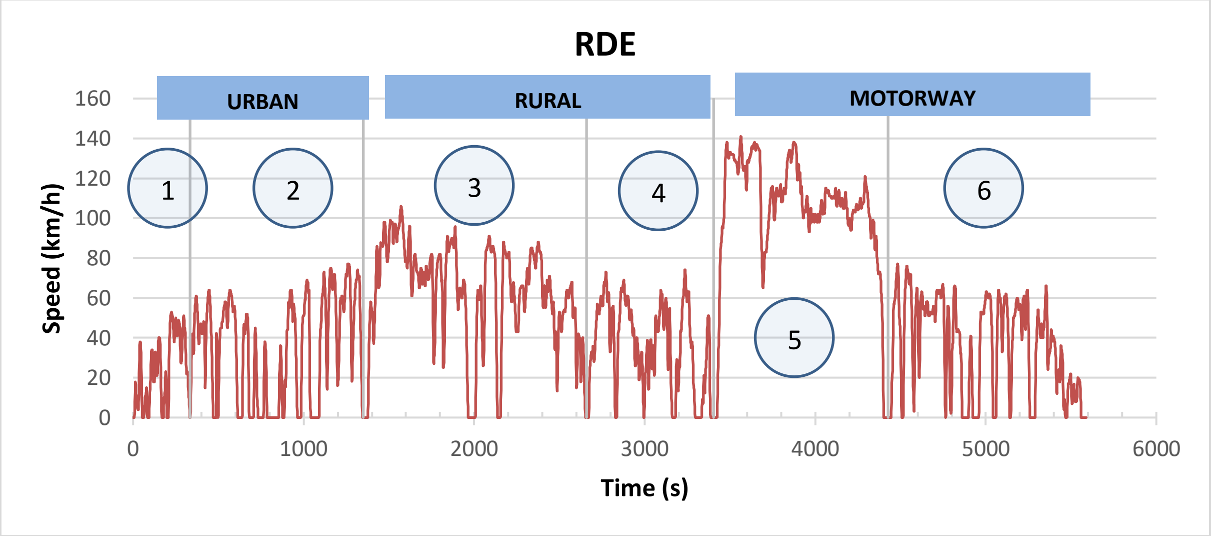
- **Cold WLTC**: WLTC is European and world approved driving cycle with cold start (Figure 3). It has four phases: (1) low – 3.1 km, (2) medium – 4.8 km, (3) high – 7.2 km and (4) extra-high – 8.3. The average speed, sampling time and driving distance is 47 km.h^{-1}, 30 minutes, and 23 km, respectively.

Figure 3. WLTC cycle



- **Hot RDE**: The RDE cycle will be a compliant driving cycle transformed for use on the chassis dynamometer test bench. It has six phases: phase 1 – 2.2 km, phase 2 – 9.6 km, phase 3 – 22.5 km, phase 4 – 7.4 km, phase 5 – 29.5 and phase 6 – 11.5. The RDE cycle represents a dynamic style of driving within the boundaries of v*a(pos). A time/speed trace of the proposed drive cycle recently used for the French Ministry of Ecology study is given Figure 4.

Figure 4. RDE cycle



V. Experimental results: emission levels

Average emissions over the full protocol

The results presented in this part and in the summary tables (Appendix 5) are **the average pollutant emissions over all the experimental tests**, described in the previous part.

Consumption, CO_2 and greenhouse gas

Emissions comparison between E10 fuel and e-fuel gasoline surrogates over the full data set shows on average a:

- 3.6 % lower fuel consumption for fuel1 and fuel2 (-0.28L / 100km), **resulting in 3.5% lower CO_2 emissions (WLTC) and 2.9% lower CO_2 emissions (RDE)**.
- Similar fuel consumption regardless of the cycle for fuel3, while a gain of 3.7% (WLTC) and 2.4% (RDE) is observed on CO_2 emissions.

Over the scope of the study where N_2O and CH_4emissions are measured, no significant impact could be assessed compared to E10 reference fuel. The GHG (greenhouse gas) gap between the fuels **remains unchanged when considering these unregulated emissions**.

Fuel consumption and CO_2 emissions are presented Figure 5 for the both WLTC and RDE driving cycles for all four fuels tested. These results are largely related to the fuel properties. Fuel1 and Fuel2 has a higher LHV than E10 fuel and fuel3 containing ethanol, which implies that for the same energy demand of the vehicle, fuel consumption will decrease proportionally due to the higher energy content of the fuel. Regarding CO_2 emissions, there is a gain regardless of the fuel. This gain is related to LHV and the higher ratio H/C of fuels. A high H/C ratio means that the fuel is less dense, and therefore has less carbon available to combine with oxygen (O_2) in the air to produce carbon dioxide (CO_2). Therefore, a fuel with a high H/C ratio will produce less CO_2 for a given volume of fuel.

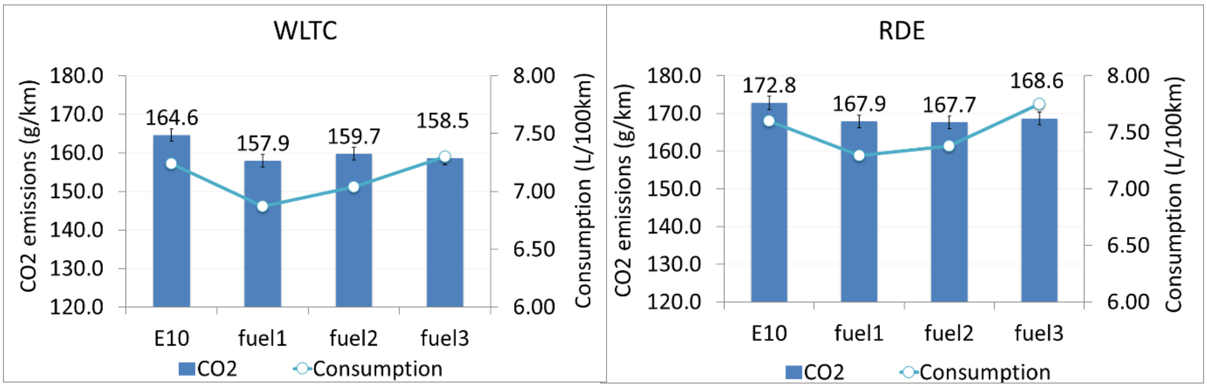


Figure 5. Comparison of CO_2 emissions and fuel consumption of E10 fuel and e-fuel gasoline surrogates over the full scope of the study. Margin of error on CO_2 emissions is of 1%. Margin of error on consumption is the standard deviation measured on the 2 tests.

Emissions of N_2O *and* CH_4

N_2O and CH_4 are greenhouse gases (GHG) emitted by internal combustion engines which must be considered in the analysis of overall vehicle pollutants. For N_2O, this campaign establishes that emissions are low and constant for all fuels regardless of the cycle (MDC ≤ 0.25 ppm). Regarding CH_4, measured values are not significant for all fuels regardless of the cycle given the minimum detectable concentration (MDC ≤ 0.5 ppm). Emissions mainly occur in the cold-start phase, within the first few minutes of the cycle. Over the rest of cycle, emissions are below the apparatus detection limit (see Appendix 2 – Emissions of N_2O and CH_4).

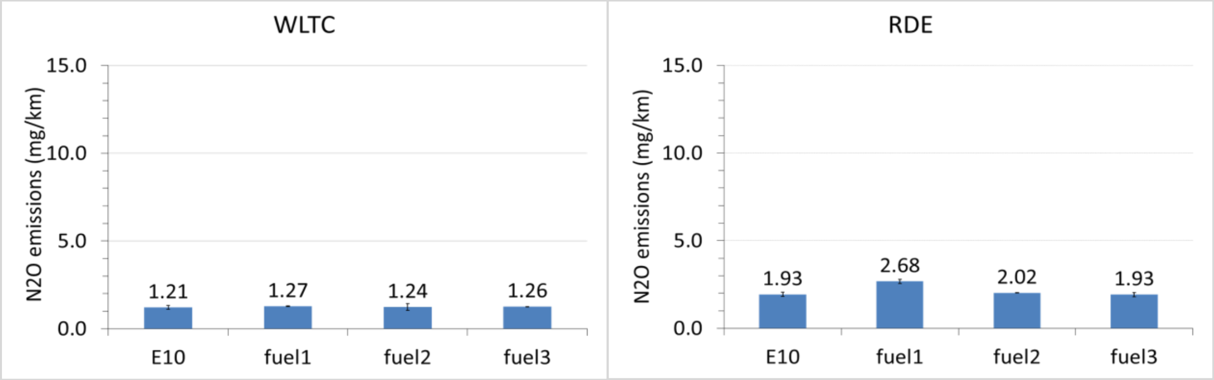


Figure 6. Comparison of N_2O emissions of E10 fuel and e-fuel gasoline surrogates over the full scope of the study. Margin of error is the standard deviation measured on the 2 tests.

Regulated local pollutants

Emissions of nitrogen oxides, NO_x

The average NO_x emissions for this study are **23 mg/km for all fuels regardless of the cycle indicating that the e-fuels tested have no impact of NOx emissions.** As a reminder, the limit of the euro 6d standard is 60 mg/km for gasoline technology vehicles.

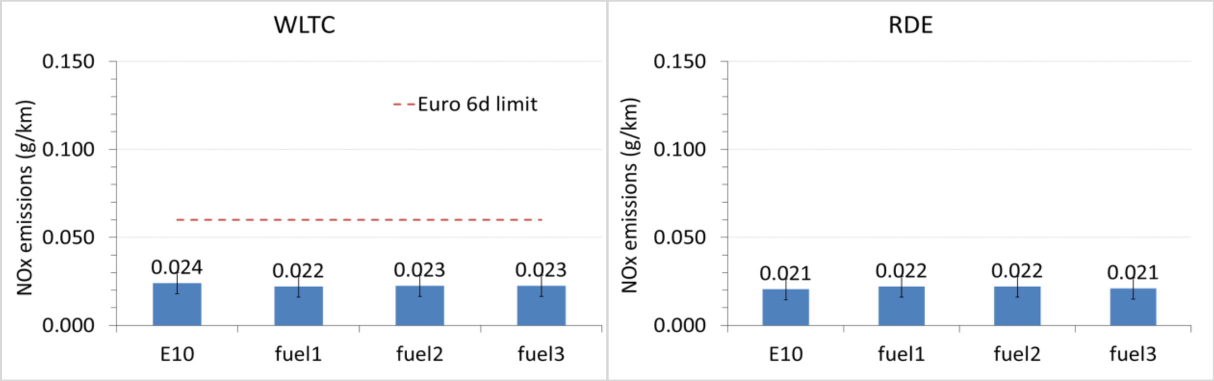


Figure 7. Comparison of NOx emissions of E10 fuel and e-fuel gasoline surrogates over the full scope of the study. The ring test analyses uncertainty is 0.006 g/km.

Regulated fine-particle emissions PN_{23}

The average fine particle emissions greater than 23 nm are $5.2*10^{10}$ #/km in E10 fuel compared to $1.1*10^{9}$ #/km in e-fuel gasoline surrogates (≈ 50 times lower). As a reminder, the limit of euro 6 standard is $6.0*10^{11}$ #/km for gasoline technology vehicles. It should be noted that this gap between E10 fuel and e-fuel gasoline surrogates is reduced significantly on the RDE cycle (7 times lower). The observed gains, respectively 97% and 85% for WLTC and RDE cycles, are mainly related to the low aromatic content of e-fuel gasoline surrogates compared to E10 fuel. Emissions levels are highly variable in E10 fuel, mainly due to low cylinder wall temperature and associated fuel condensation. This leads to rich combustion areas and high particulate emissions at cold start.

Average PN_{23} emission level for e-gasoline surrogates decreased down to $1.1*10^9$ #/km, 97% less than E10 fuel in this study on the WLTC test, a reduction of 87% was witnessed on the RDE test cycle.

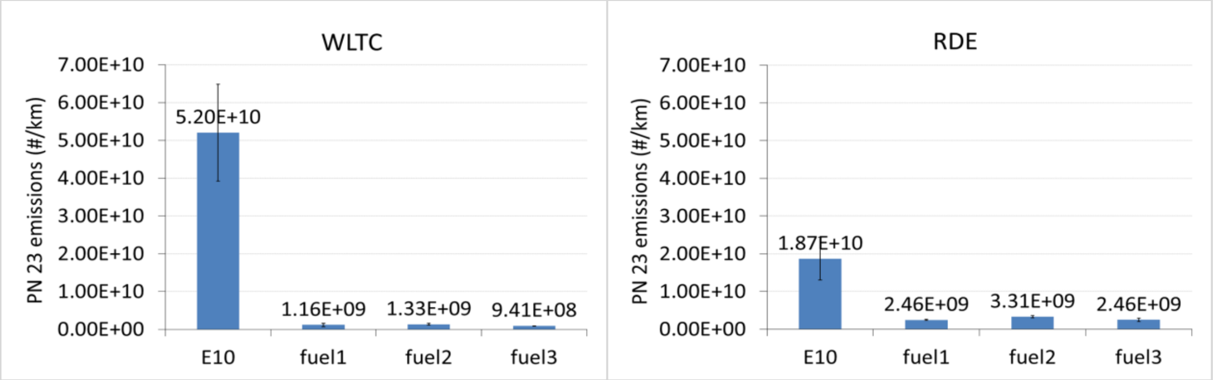


Figure 8. Comparison of number of particulate emissions over 23 nm of E10 fuel and e-fuel gasoline surrogates over the full scope of the study. Margin of error is the standard deviation measured on the 2 tests.

Particulate matter emissions, PM

PM emissions are low regardless of the fuel and driving cycle. As a reminder, the limit of euro 6 standard is 4.5 mg/km for gasoline technology vehicles. Emissions Measurements in this study are close to 0.1 mg/km. No fuel effect can be discussed as the uncertainty of PM measurement is an order of magnitude higher than the reported concentration (i.e. 0.989 mg/km).

Unburnt hydrocarbon emissions, HC and carbon monoxide CO

In this study, HC **emissions are close to 12 mg/km for e-fuel gasoline surrogates compared to 17 mg/km for E10 fuel on WLTC cycle.** Emissions **are lower on the RDE cycle and the difference between fuels is not discernible**. As a reminder, the limit of the Euro 6 standard is 100 mg/km of HC for gasoline vehicles.

In the case of CO emissions, e-fuel -gasoline surrogates are responsible for an non negligeable increase compared to E10 fuel with average emissions of 176 mg/km against 70 mg/km for E10 fuel on WLTC cycle; as a reminder, the CO limit of the Euro 6 standard is 1000 mg/km for gasoline vehicles. It should be noted that **this increasing trend is not observed on the RDE cycle**. This can be explained by the fact that the cold phase (the most emissive phase, see Figure 11) of the RDE cycle represents only 3% of the total cycle compared to 13.5% for the WLTC cycle. Consequently, the trend towards higher *CO* emissions is less visible in the RDE cycle. Regarding CO engine out emissions on WLTC cycle, the difference is limited even if a slight increase is observed with alternative fuels to which may be related to unoptimized engine calibration.

On WLTC cycle, catalyst operation seems to be delayed with the e-fuel -gasoline surrogates compared to E10. CO emissions are **mostly increased during the first few seconds of the cycle** (see Appendix 3 – Instantaneous *CO* emissions). As illustrated Figure 11, RDE cycle confirms a tendency to increase *CO* emission during the cold phase. This could be due to:

- a delay in ignition due to a modified exhaust enthalpy

- an increased production of *CO* from combustion by the fuel in question, itself possibly due to an inadequacy of the injection/supercharging settings to the properties of the fuel or its intrinsic properties
- both together

Please note that these are only assumptions.

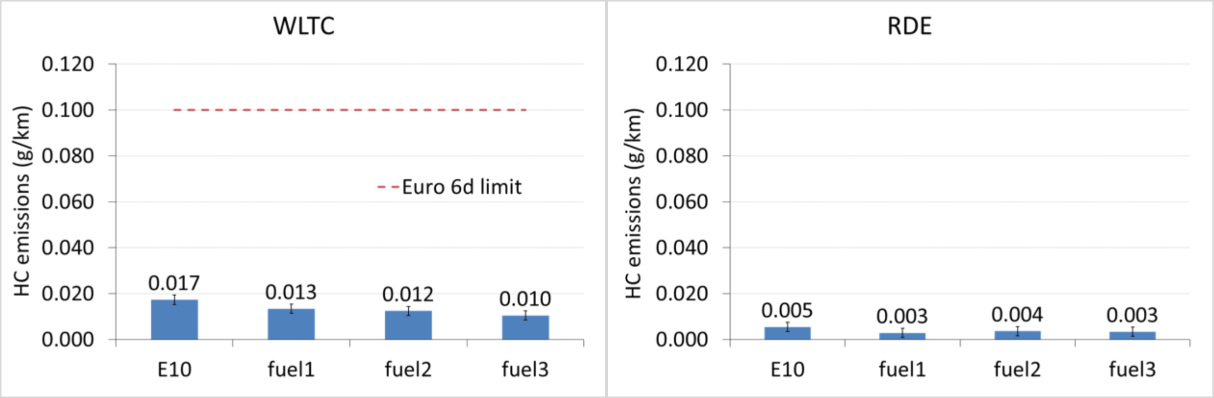


Figure 9. Comparison of HC emissions of E10 fuel and e-fuel gasoline surrogates over the full scope of the study. The ring test analyses uncertainty is 0.002 g/km.

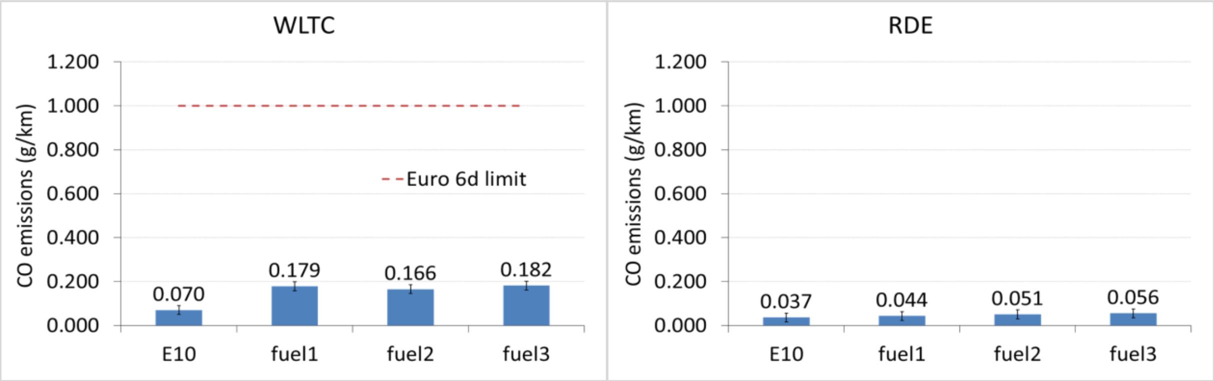


Figure 10. Comparison of CO emissions of E10 fuel and e- fuel gasoline surrogates over the full scope of the study. The ring test analyses uncertainty is 0.02 g/km.

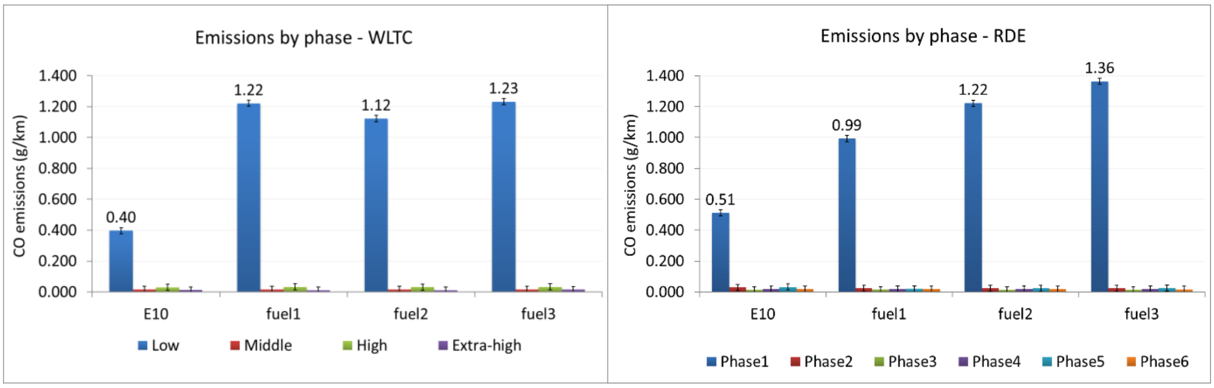


Figure 1. Comparison of CO emissions by phase of E10 fuel and e-fuel gasoline surrogates over the full scope of the study. Margin of error is the standard deviation measured on the 2 tests.

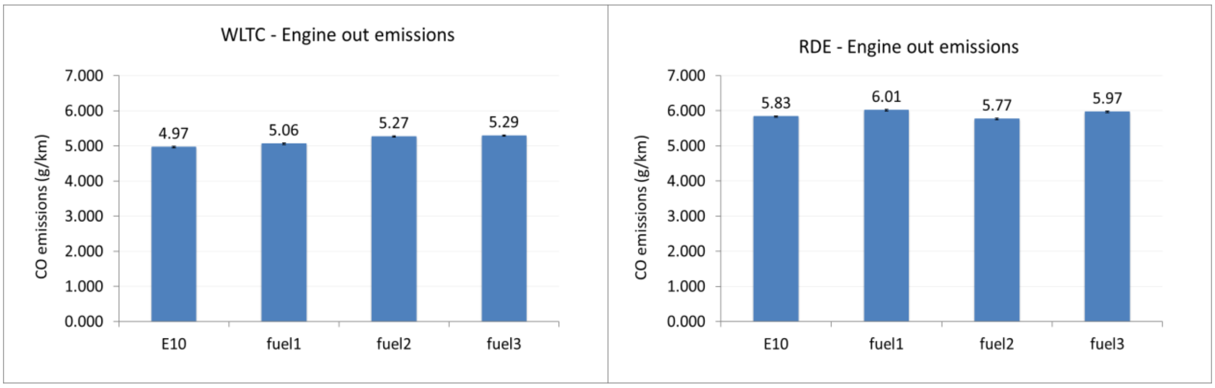


Figure 12. Comparison of CO engine out emissions of E10 fuel and e-fuel gasoline surrogates over the full scope of the study. The ring test analyses uncertainty is 0.02 g/km.

Unregulated pollutants

NH_3 ammonia emissions

NH_3 emissions are not part of the regulatory framework of the Euro 6 standard but will be considered for regulation as part of Euro 7. NH_3 emissions contribute to the degradation of air quality as **precursors of secondary particles and as a toxic gas for humans above a certain concentration threshold**.

In the case of gasoline, ammonia is a reaction product within the 3-way catalytic converters (TWCs) through *in situ* production of hydrogen during excursions into rich engine operation (cold start, high acceleration or driving at high speed).

In the experimental scope of the study, **no clear trend is observed on WLTC cycle regarding** NH_3 emissions. Emissions are low but above the minimum detectable concentration (MDC ≤ 0.25 ppm) and mainly take place in the cold phase, where the standard deviation is higher. Indeed, despite all the efforts made to repeat the soaking protocol as well as the fuel purge, it cannot be excluded that the start-up is subject to random effects or variable behavior of the aftertreatment system. This implies a higher variability in cold emissions, where, moreover, emissions are often higher (Figure 14)[3]. Similar trends for NH_3 have been observed in other studies, including for different measurement techniques and vehicles. **On RDE cycle**, fuel2 and fuel3 contribute to higher emissions than E10 and fuel1 (two times higher).

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[3] Please refer to the section Test cycles for details of phases

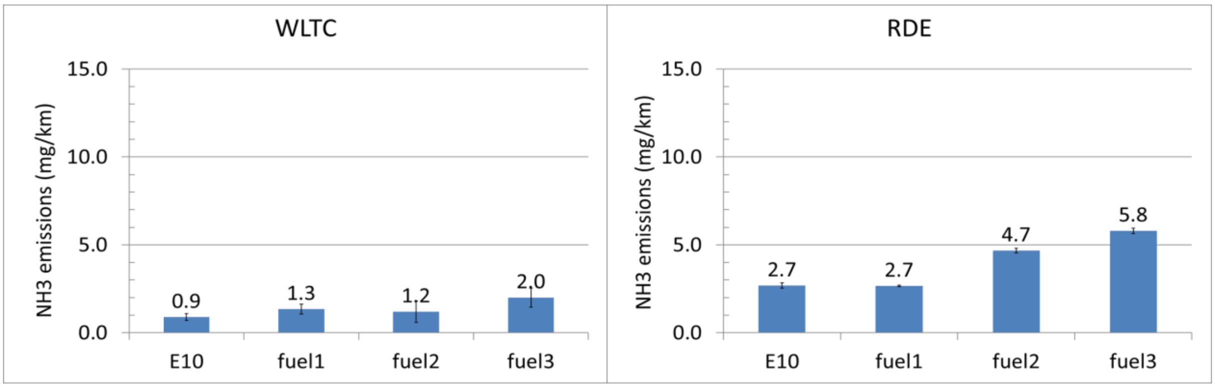


Figure 13. Comparison of NH_3 emissions of E10 fuel and e-fuel gasoline surrogates over the full scope of the study. Margin of error is the standard deviation measured on the 2 tests.

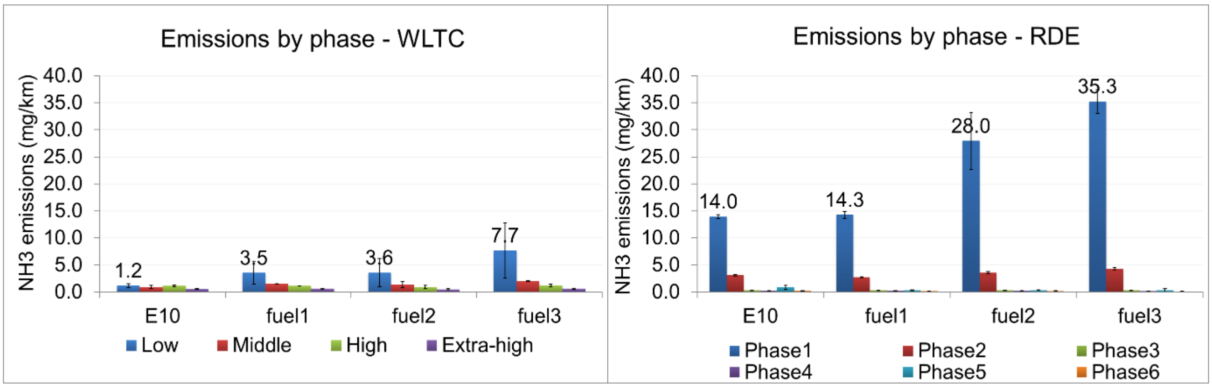


Figure 14. Comparison of NH_3 emissions by phase of E10 fuel and e-fuel gasoline surrogates over the full scope of the study. Margin of error is the standard deviation measured on the 2 tests.

Aldehydes emissions

Aldehydes are not part of the regulatory framework of the Euro 6 standard. Exposure to aldehydes presents a **significant health risk, as they are genotoxic agents: Aldehydes can cause nasopharyngeal cancer in humans and have been shown to instigate respiratory carcinomas in rodent models.**

In the case aldehydes emitted out of gasoline vehicles, predominantly formaldehyde and acetaldehyde is emitted. Occurring primarily during the cold-start phase and are the result of the incomplete burning and oxidation of hydrocarbons.

Regarding **formaldehyde emissions, measured values are not significant for all fuels regardless of the cycle given the minimum detectable concentration (MDC ≤ 2.5 ppm)**. Emissions mainly occur in the cold-start phase, within the first few minutes of the cycle. Over the rest of cycle, emissions are below the apparatus detection limit of 2.5 ppm (see Appendix 2 – Instantaneous formaldehyde emissions). It should be noted that e-fuel gasoline surrogates contribute to decrease the cold phase emissions compared to E10 fuel (Figure 15)[3]:

- **48 % lower formaldehyde emissions** (WLTC) and **67 % lower formaldehyde emissions** (RDE) **for fuel1**
- **39 % lower formaldehyde emissions (**WLTC) and **32 % lower formaldehyde emissions** (RDE) **for fuel2**
- **62 % lower formaldehyde emissions** (WLTC) and **66 % lower formaldehyde emissions** (RDE) **for fuel3**

In the case of **acetaldehyde emissions, measured values are not significant for all fuels regardless of the cycle given the minimum detectable concentration (MDC ≤ 2.5 ppm).** As for formaldehyde, emissions mainly occur in the cold-start phase, in the first few minutes of the cycle. Over the rest of cycle, emissions are below the apparatus minimum detectable concentration of 2.5 ppm. It should be noted that fuel effect is of first order; e-fuel gasoline surrogates contribute to decrease the cold phase emissions compared to E10 fuel (Figure 16)[3]:

- **81 % lower formaldehyde emissions** (WLTC) and **79 % lower formaldehyde emissions** (RDE) **for fuel1**
- **81 % lower formaldehyde emissions (**WLTC) and **72 % lower formaldehyde emissions** (RDE) **for fuel2**
- **37 % lower formaldehyde emissions** (WLTC) and **54 % lower formaldehyde emissions** (RDE) **for fuel3**

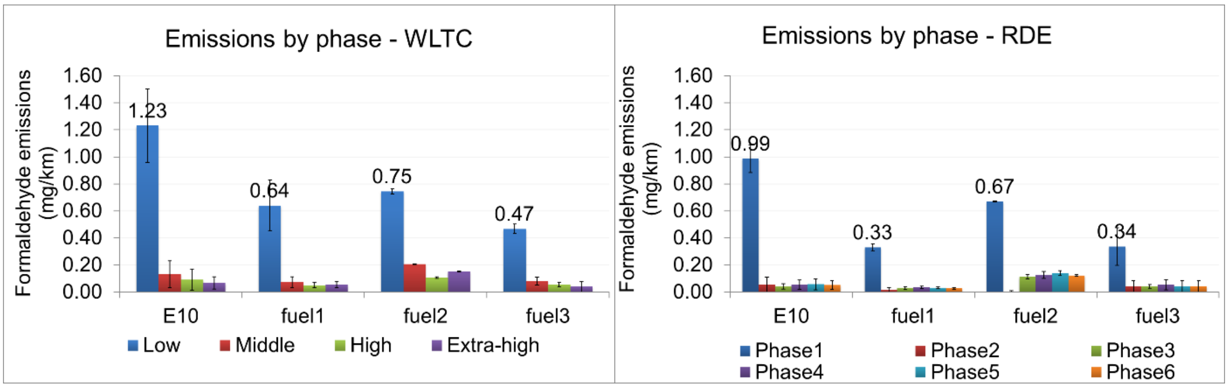


Figure 15. Comparison of formaldehyde emissions by phase of E10 fuel and e-fuel gasoline surrogates over the full scope of the study. Margin of error is the standard deviation measured on the 2 tests

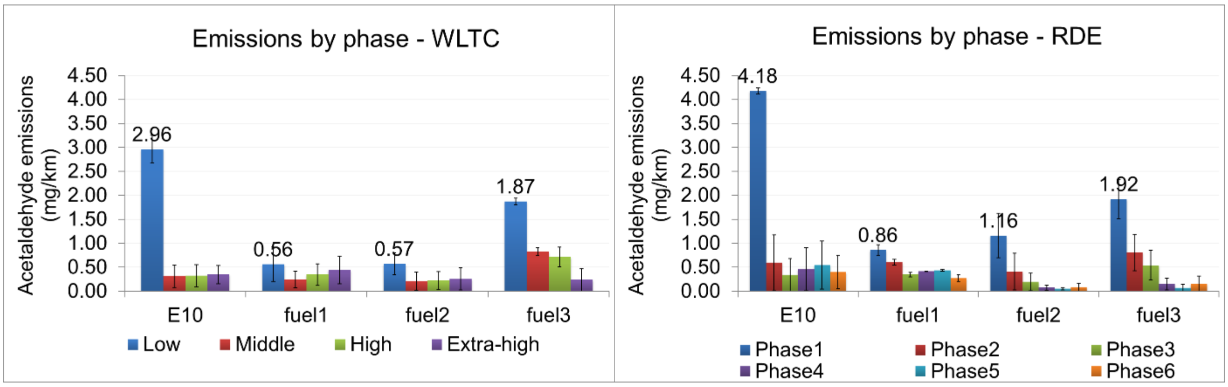


Figure 16. Comparison of formaldehyde emissions by phase of E10 fuel and e-fuel gasoline surrogates over the full scope of the study. Margin of error is the standard deviation measured on the 2 tests.

Unregulated particle emissions PN_{10}

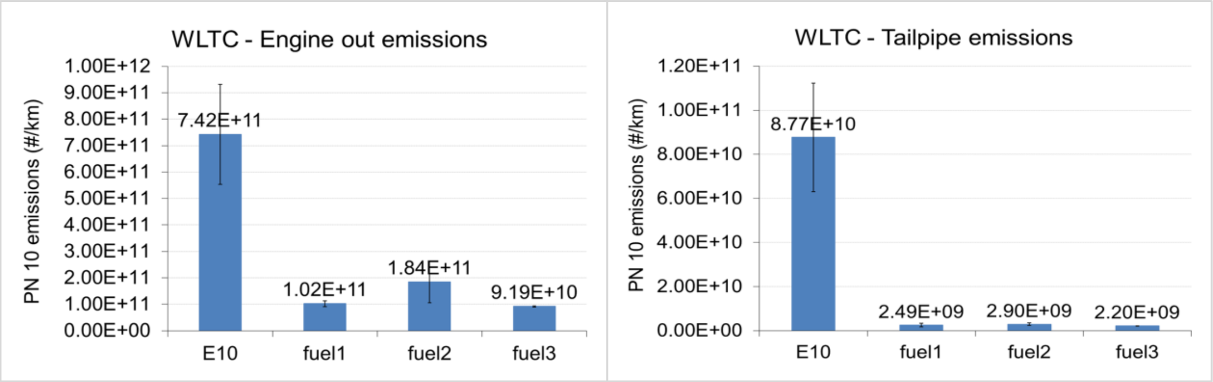


Figure 17. Comparison of number of particulate emissions over 10 nm of E10 fuel and e-fuel gasoline surrogates (WLTC) over the full scope of the study. Margin of error is the standard deviation measured on the 2 tests.

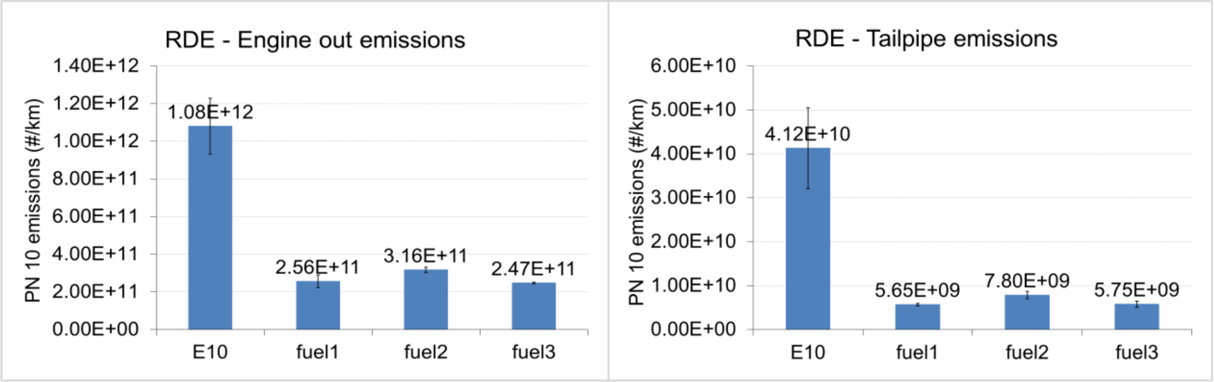


Figure 18. Comparison of number of particulate emissions over 10 nm of E10 fuel and e-fuel gasoline surrogates (RDE) over the full scope of the study. Margin of error is the standard deviation measured on the 2 tests.

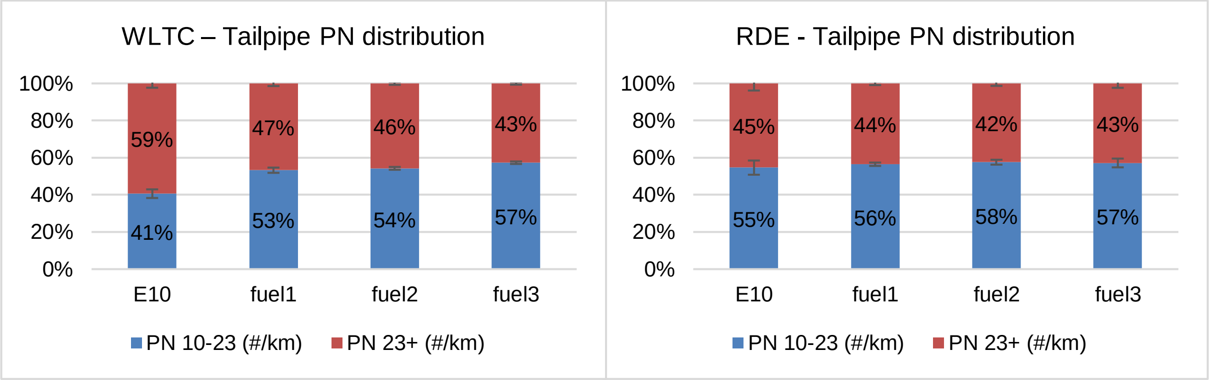


Figure 19. Tailpipe distribution of PN emissions of E10 fuel and e-fuel gasoline surrogates over the full scope of the study. Margin of error is the standard deviation measured on the 2 tests.

GPF enables **a particle number decrease up to two orders of magnitude** regardless of the cycle. **The fuel impact remains visible with an order of the magnitude less for PN_{10} with e-fuel gasoline surrogates compared to E10.**

In addition, the share of particles with sizes ranging from 10 nm to 23 nm among all the PN10 emitted (i.e. all particles of size above 10 nm) is slightly higher for e-fuel gasoline surrogates than for E10. Indeed, it is around 55% for the e-fuel gasoline surrogates versus 41% for E10 fuel.

VI. Conclusion

The present work was conducted for Transport & Environment to evaluate emissions of potential e-fuel formulations available by 2030. A fuel matrix including one commercially available E10 fuel as well as three low aromatic fuels were selected. Based on our current knowledge as well as on the limitations that exist for internal combustion engines, there three low aromatic formulations appear as potentially compatible with future liquid gasoline fuels produced from e-fuel processes.

The fuel emissions and consumption were evaluated on a recent spark ignited vehicle (regulated and non-regulated emissions). The work was carried out with **1 recent (Euro 6d) vehicle**, a Mercedes A Class, on WLTC and RDE drive cycles performed on a chassis dyno, on **standard pollutant emissions as well as CO_2, aldehydes, N_2O, and NH_3 emissions**.

The results have shown that all formulated fuels respect the EN228 standard, except for volatility and distillation which are higher than EN228 limits.

Compliance with emission standards

With no exception, this experimental campaign shows that the vehicle complies with the normative thresholds. It is worth noting the **3.6% gain in consumption** (WLTC cycle) for fuel1 and fuel2 (without ethanol). This result is largely related to the fuel properties. Non-oxygenated fuels have a higher net calorific value in volume than oxygenated fuels, which implies that for the same energy demand from the vehicle, the fuel consumption by volume will decrease. Following the trend observed for fuel consumption, a gain of **3.6% on CO_2 emissions** (WLTC cycle) is observed. Finally, it should be emphasized that a gain of more than **90% on PN_{23} emissions** (WLTC cycle) is observed certainly due to the low aromatic content.

Impact of Non-Regulated Pollutants (NRP)

For the N_2O and formaldehyde, this campaign establishes that emissions are low and constant for all fuels given the incertainty regardless of the cycle. Regarding NH_3, no clear trend is observed on WLTC cycle, while on RDE cycle, fuel2 and fuel3 contribute to higher emissions than E10 and fuel1. In the case of acetaldehyde emissions, despite low emissions, E10 and fuel3 (containing 10%v/v of ethanol) seems to be responsible of higher emissions than the other fuels. Similarly, to regulated PN_{23} emissions, a decrease of more than 90% on PN_{10} emissions (WLTC) is also observed.

Significant difference between tailpipe and engine out emissions

With a few exceptions, this experimental campaign shows that conclusions drawn engine out are also valid at tailpipe. The exception is CO emissions where the difference between the fuels is less pronounced engine out even if a slight increase is observed with alternative fuels which may be related to unoptimized engine calibration. Regarding PN_{10} emissions, GPF allows a reduction by one to two orders of magnitude regardless of the cycle. The fuel impact remains visible for tailpipe emissions with an order of magnitude less of PN_{10} for alternative fuels compared to E10.

Increase in urban use

Emissions levels are significantly higher in urban use whatever the fuel is, especially aldehydes and N_2O emissions:

- 3 to 5 times higher for formaldehyde considering the standard urban WLTC phases compared to full WLTC type driving. Regarding acetaldehyde emissions, fuels with ethanol seem to emit more in the urban phase compared to full WLTC cycle (2 to 4 times higher).
- 5 times higher for N_2O considering the standard urban WLTC phases compared to full WLTC type driving.

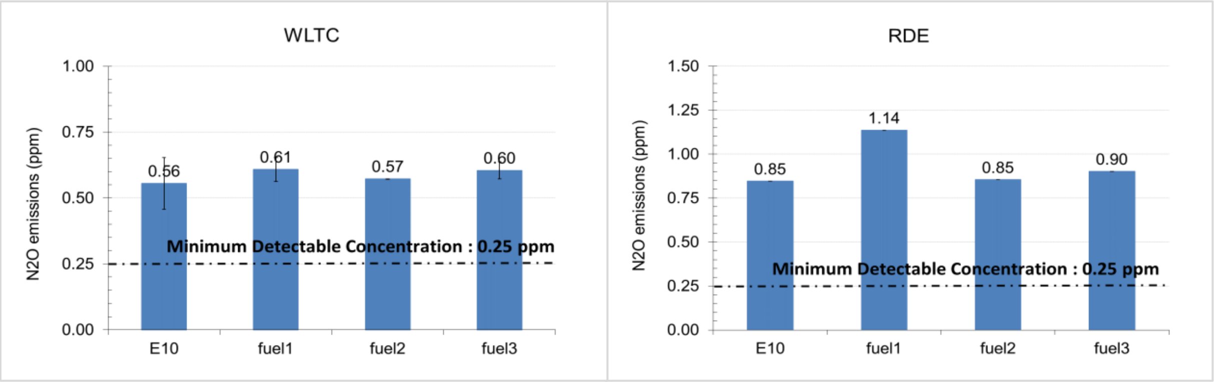
These emission levels are even higher by focusing on conditions more representative of urban use (very short and slow journeys).

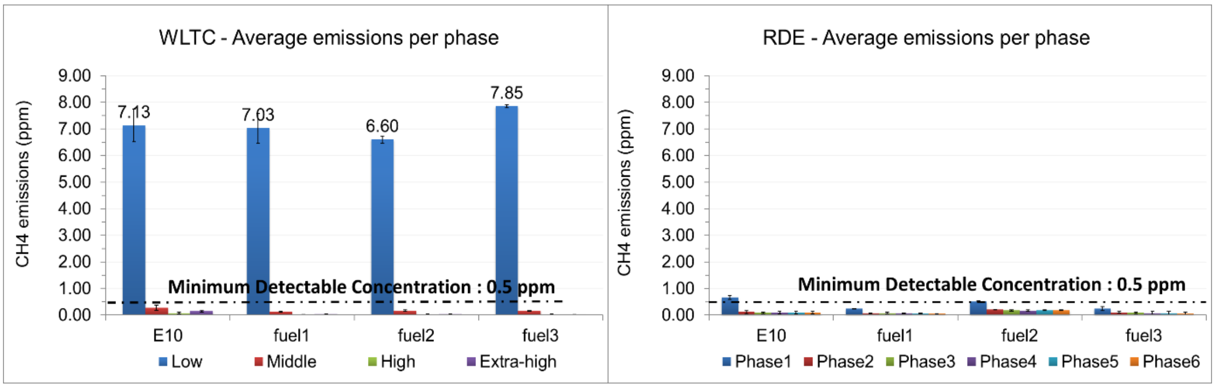
VII. Appendices

Appendix 1 – Characteristics of the FTIR analyzer

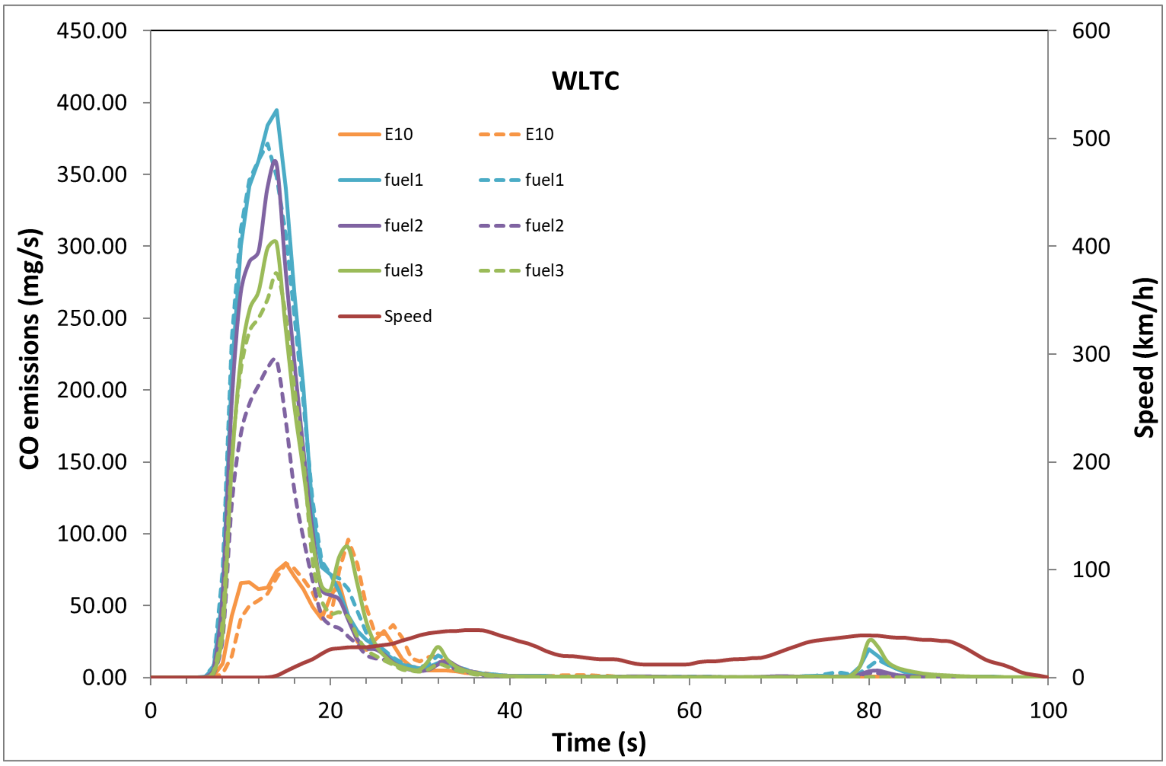
AVL SESAM FTIR	
Acquisition frequency	= 1 or 5 Hz
Spectral analysis area	= 650 to 4000 cm^{-1}
Wavelength resolution	= 0.5 cm^{-1}
Spectrometer response time (T90 – T10)	≈ 1s
Accuracy	≤ +/- 2% MV ± 0.5 x MDC
Linearity	≤ +/- 2% MV or ≤ 1% of scale
Drift Offset & Gain	≤ +/- 2 x MDC / week
Heated sampling and measuring cell	≈ 190 °C
Measuring cell	Multi-reflection • V = 200 ml → optical path = 2 m
Detector • LN_2 cooled and automatic filling device	MCT
Materials in contact with the gas	Stainless steel, Teflon, ZnSe, Gold plated aluminum
Sample flow (pressure regulator integrated in pre-filter)	≈ 8-10 l/min
Communication via AK protocol or analogue I/O	OK
Functional gas via dedicated purge air generator or N_2 cylinder	OK
Weight	≈ 200 kg

Appendix 2 – Emissions of N_2O and CH_4

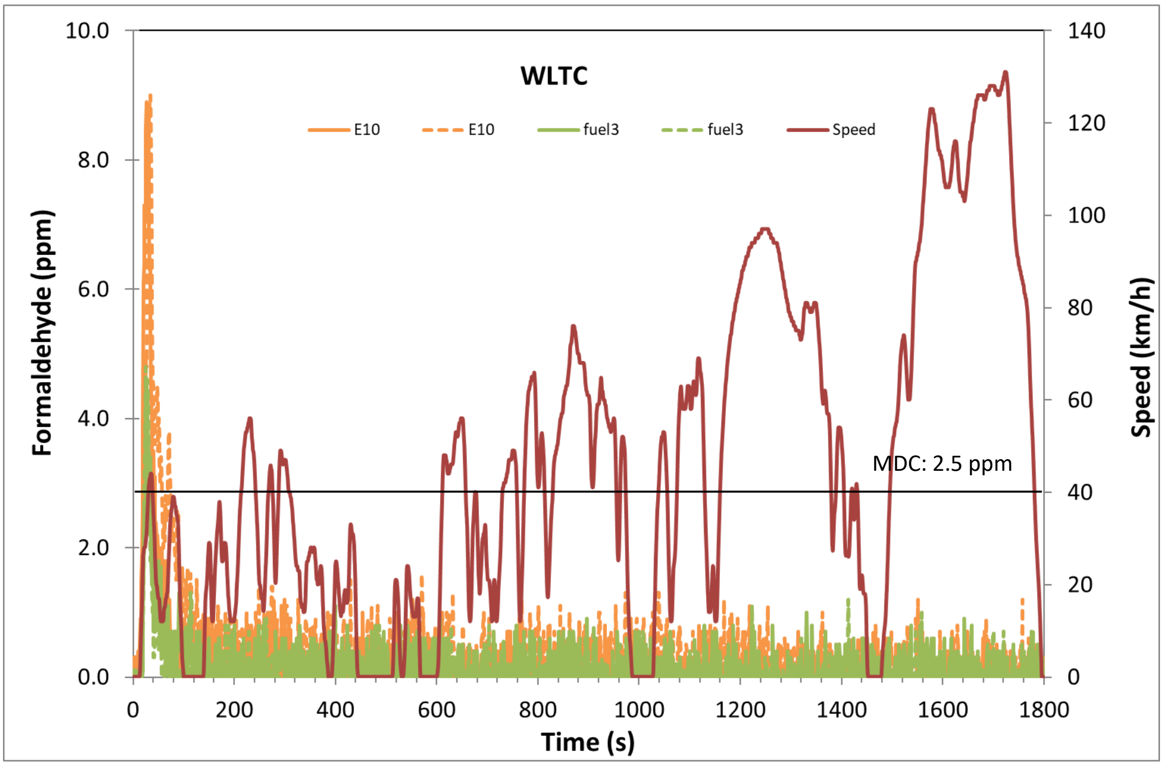


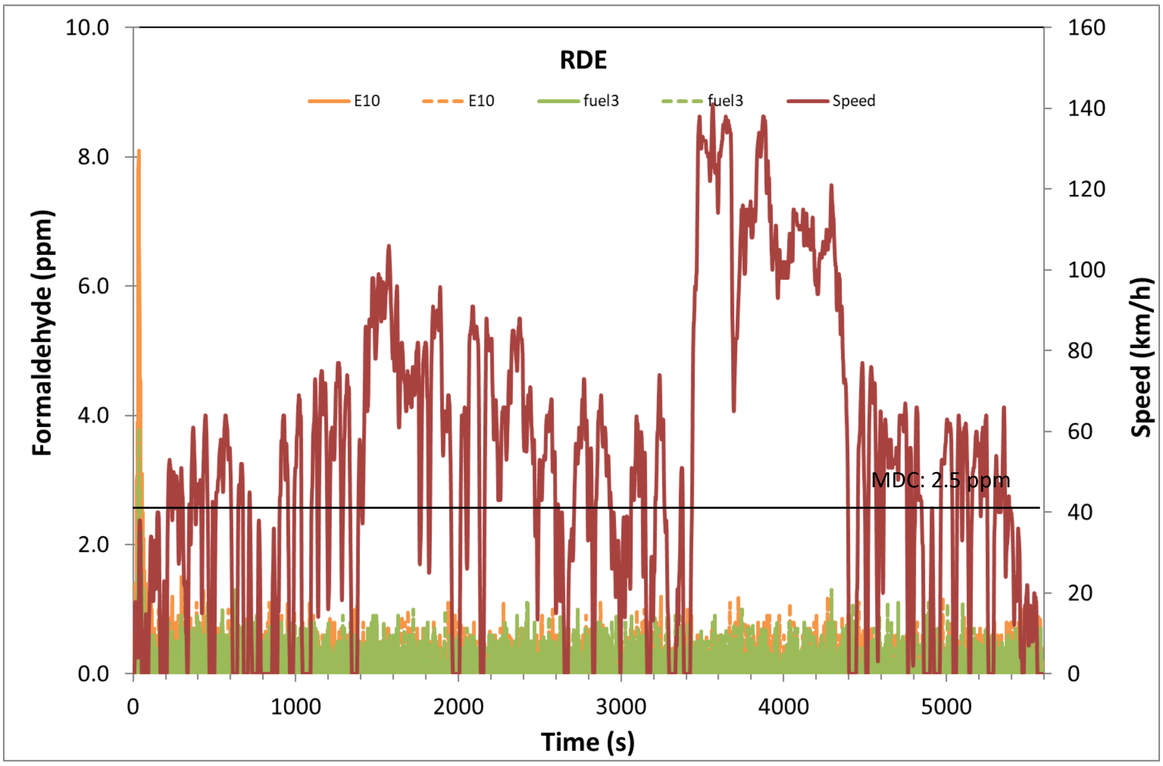


Appendix 3 – Instantaneous *CO* emissions



Appendix 4 – Instantaneous formaldehyde emissions





Appendix 5 – Summary of the emission test results

Consumption, CO_2, and greenhouse gas

Tailpipe

		Fuel consumption (L/100km)					Fuel consumption (L/100km)						
Fuel	**Test**	**Low**	**Middle**	**High**	**Extra-high**	**WLTC**	**Phase1**	**Phase2**	**Phase3**	**Phase4**	**Phase5**	**Phase6**	**RDE**
E10	Test 1	10.89	7.27	6.14	6.90	7.27	10.42	9.93	6.27	7.45	7.87	7.07	7.59
	Test 2	10.62	7.24	6.14	6.87	7.21	10.37	10.01	6.31	7.43	7.83	7.20	7.61
	Mean	**10.76**	**7.26**	**6.14**	**6.89**	**7.24**	**10.40**	**9.97**	**6.29**	**7.44**	**7.85**	**7.14**	**7.60**
fuel1	Test 1	10.15	6.81	5.84	6.57	6.87	9.98	9.51	6.09	7.19	7.54	7.00	7.33
	Test 2	10.05	6.86	5.88	6.57	6.87	10.12	9.47	6.00	7.10	7.47	6.91	7.26
	Mean	**10.10**	**6.84**	**5.86**	**6.57**	**6.87**	**10.05**	**9.49**	**6.05**	**7.15**	**7.51**	**6.96**	**7.30**
fuel2	Test 1	10.47	7.03	5.97	6.70	7.04	10.21	9.64	6.14	7.22	7.68	7.04	7.42
	Test 2	10.48	7.04	5.99	6.68	7.04	10.29	9.76	6.10	7.28	7.60	6.55	7.34
	Mean	**10.48**	**7.04**	**5.98**	**6.69**	**7.04**	**10.25**	**9.70**	**6.12**	**7.25**	**7.64**	**6.80**	**7.38**
fuel3	Test 1	10.79	7.32	6.26	6.85	7.29	10.62	10.09	6.42	7.71	8.00	7.42	7.77
	Test 2	10.71	7.34	6.22	6.97	7.31	10.65	10.08	6.41	7.58	7.94	7.37	7.73
	Mean	**10.75**	**7.33**	**6.24**	**6.91**	**7.30**	**10.64**	**10.09**	**6.42**	**7.65**	**7.97**	**7.40**	**7.75**

		CO2 (g/km)					CO2 (g/km)						
Fuel	**Test**	**Low**	**Middle**	**High**	**Extra-high**	**WLTC**	**Phase1**	**Phase2**	**Phase3**	**Phase4**	**Phase5**	**Phase6**	**RDE**
E10	Test 1	246.8	165.4	139.7	157.0	165.2	235.9	225.9	142.7	169.5	178.9	160.8	172.6
	Test 2	240.6	164.7	139.6	156.2	164.0	234.5	227.6	143.6	168.9	178.0	163.9	173.1
	Mean	**243.7**	**165.1**	**139.6**	**156.6**	**164.6**	**235.2**	**226.7**	**143.2**	**169.2**	**178.4**	**162.3**	**172.8**
fuel1	Test 1	231.6	156.8	134.5	151.3	157.8	228.2	219.0	140.2	165.6	173.6	161.2	168.7
	Test 2	229.1	157.9	135.4	151.3	158.0	231.0	218.0	138.2	163.5	172.0	159.0	167.1
	Mean	**230.3**	**157.4**	**135.0**	**151.3**	**157.9**	**229.6**	**218.5**	**139.2**	**164.6**	**172.8**	**160.1**	**167.9**
fuel2	Test 1	235.4	159.7	135.6	152.2	159.6	229.8	219.1	139.5	164.0	174.6	160.0	168.6
	Test 2	236.5	160.0	136.1	151.9	159.8	231.5	221.7	138.7	165.5	172.7	148.8	166.7
	Mean	**236.0**	**159.9**	**135.9**	**152.1**	**159.7**	**230.7**	**220.4**	**139.1**	**164.8**	**173.6**	**154.4**	**167.7**
fuel3	Test 1	232.6	159.4	136.2	149.0	158.2	229.1	219.5	139.7	167.9	174.0	161.5	169.1
	Test 2	231.1	159.8	135.4	151.8	158.9	229.1	219.4	139.5	164.9	172.8	160.5	168.2
	Mean	**231.9**	**159.6**	**135.8**	**150.4**	**158.5**	**229.1**	**219.4**	**139.6**	**166.4**	**173.4**	**161.0**	**168.6**

		N2O (mg/km)					N2O (mg/km)						
Fuel	**Test**	**Low**	**Middle**	**High**	**Extra-high**	**WLTC**	**Phase1**	**Phase2**	**Phase3**	**Phase4**	**Phase5**	**Phase6**	**RDE**
E10	Test 1	6.97	0.25	0.10	0.27	1.10	10.88	0.61	0.28	0.31	0.37	0.32	0.63
	Test 2	6.47	0.67	0.46	0.51	1.32	11.31	0.87	0.52	0.61	0.59	0.57	0.88
	Mean	**6.72**	**0.46**	**0.28**	**0.39**	**1.21**	**11.09**	**0.74**	**0.40**	**0.46**	**0.48**	**0.45**	**1.93**
fuel1	Test 1	7.22	0.45	0.32	0.43	1.29	18.00	0.92	0.53	0.65	0.64	0.73	1.11
	Test 2	6.86	0.60	0.32	0.36	1.25	13.99	0.74	0.43	0.51	0.51	0.55	0.87
	Mean	**7.04**	**0.52**	**0.32**	**0.40**	**1.27**	**16.00**	**0.83**	**0.48**	**0.58**	**0.58**	**0.64**	**2.68**
fuel2	Test 1	7.96	0.66	0.33	0.39	1.43	9.65	0.73	0.37	0.46	0.49	0.52	0.72
	Test 2	6.01	0.43	0.23	0.27	1.05	14.71	0.54	0.27	0.39	0.32	0.30	0.71
	Mean	**6.99**	**0.55**	**0.28**	**0.33**	**1.24**	**12.18**	**0.64**	**0.32**	**0.43**	**0.41**	**0.41**	**2.02**
fuel3	Test 1	7.07	0.47	0.33	0.36	1.26	10.67	0.74	0.44	0.22	0.00	0.00	0.50
	Test 2	7.31	0.42	0.28	0.36	1.27	12.08	0.60	0.42	0.46	0.39	0.45	0.74
	Mean	**7.19**	**0.45**	**0.31**	**0.36**	**1.26**	**11.38**	**0.67**	**0.43**	**0.34**	**0.20**	**0.22**	**1.93**

		CH4 (mg/km)					CH4 (mg/km)						
Fuel	**Test**	**Low**	**Middle**	**High**	**Extra-high**	**WLTC**	**Phase1**	**Phase2**	**Phase3**	**Phase4**	**Phase5**	**Phase6**	**RDE**
E10	Test 1	10.24	0.09	0.00	0.04	1.39	**10.83**	**0.80**	**0.38**	**0.22**	**1.58**	**0.11**	**1.08**

	Test 2	9.68	0.00	0.00	0.31	1.39	14.26	0.92	0.38	0.22	1.36	0.66	1.18
	Mean	**9.96**	**0.05**	**0.00**	**0.18**	**1.39**	**12.55**	**0.86**	**0.38**	**0.22**	**1.47**	**0.39**	**1.13**
fuel1	Test 1	9.17	0.09	0.00	0.08	1.25	8.86	0.35	0.19	0.22	0.64	0.33	0.62
	Test 2	9.38	0.18	0.00	0.08	1.30	9.59	0.12	0.13	0.00	0.57	0.22	0.53
	Mean	**9.28**	**0.14**	**0.00**	**0.08**	**1.28**	**9.23**	**0.24**	**0.16**	**0.11**	**0.61**	**0.28**	**0.58**
fuel2	Test 1	11.77	0.18	0.00	0.12	1.63	11.64	0.57	0.13	0.11	0.60	0.44	0.69
	Test 2	9.26	0.27	0.00	0.08	1.30	13.01	0.80	0.13	0.22	0.71	0.33	0.78
	Mean	**10.52**	**0.23**	**0.00**	**0.10**	**1.47**	**12.33**	**0.69**	**0.13**	**0.17**	**0.66**	**0.39**	**0.74**
fuel3	Test 1	10.16	0.27	0.00	0.00	1.40	9.88	0.35	0.13	0.22	0.61	0.22	0.60
	Test 2	9.97	0.27	0.00	0.12	1.42	12.99	0.23	0.19	0.11	0.65	0.33	0.70
	Mean	**10.07**	**0.27**	**0.00**	**0.06**	**1.41**	**11.44**	**0.29**	**0.16**	**0.17**	**0.63**	**0.28**	**0.65**

Regulated local pollutants

Tailpipe

		NOx (g/km)					**NOx (g/km)**						
Fuel	**Test**	**Low**	**Middle**	**High**	**Extra-high**	**WLTC**	**Phase1**	**Phase2**	**Phase3**	**Phase4**	**Phase5**	**Phase6**	**RDE**
E10	Test 1	0.110	0.015	0.009	0.006	0.023	0.152	0.028	0.016	0.017	0.009	0.026	0.020
	Test 2	0.126	0.015	0.009	0.006	0.025	0.188	0.026	0.017	0.017	0.010	0.024	0.021
	Mean	**0.118**	**0.015**	**0.009**	**0.006**	**0.024**	**0.170**	**0.027**	**0.017**	**0.017**	**0.010**	**0.025**	**0.021**
fuel1	Test 1	0.117	0.011	0.004	0.004	0.020	0.187	0.030	0.018	0.018	0.009	0.030	0.022
	Test 2	0.130	0.011	0.008	0.007	0.024	0.178	0.024	0.019	0.018	0.009	0.031	0.022
	Mean	**0.124**	**0.011**	**0.006**	**0.006**	**0.022**	**0.183**	**0.027**	**0.019**	**0.018**	**0.009**	**0.031**	**0.022**
fuel2	Test 1	0.108	0.014	0.007	0.006	0.021	0.201	0.031	0.018	0.017	0.010	0.034	0.024
	Test 2	0.126	0.014	0.009	0.005	0.024	0.173	0.032	0.015	0.014	0.010	0.021	0.020
	Mean	**0.117**	**0.014**	**0.008**	**0.006**	**0.023**	**0.187**	**0.032**	**0.017**	**0.016**	**0.010**	**0.028**	**0.022**
fuel3	Test 1	0.109	0.016	0.008	0.007	0.023	0.134	0.030	0.018	0.019	0.010	0.035	0.022
	Test 2	0.102	0.017	0.008	0.007	0.022	0.126	0.029	0.016	0.019	0.008	0.033	0.020
	Mean	**0.106**	**0.017**	**0.008**	**0.007**	**0.023**	**0.130**	**0.030**	**0.017**	**0.019**	**0.009**	**0.034**	**0.021**

		PN23 (#/km)					**PN23 (#/km)**						
Fuel	**Test**	**Low**	**Middle**	**High**	**Extra-high**	**WLTC**	**Phase1**	**Phase2**	**Phase3**	**Phase4**	**Phase5**	**Phase6**	**RDE**
E10	Test 1	4.30E+11	1.42E+09	1.35E+09	1.55E+09	6.48E+10	1.64E+11	8.88E+09	4.78E+09	3.96E+09	1.50E+10	4.22E+09	1.30E+10
	Test 2	2.44E+11	1.50E+09	1.70E+09	1.76E+09	3.93E+10	4.48E+11	1.71E+10	8.34E+09	3.88E+09	2.04E+10	3.86E+09	2.44E+10
	Mean	**3.37E+11**	**1.46E+09**	**1.53E+09**	**1.65E+09**	**5.20E+10**	**3.06E+11**	**1.30E+10**	**6.56E+09**	**3.92E+09**	**1.77E+10**	**4.04E+09**	**1.87E+10**
fuel1	Test 1	8.55E+08	1.49E+08	1.89E+08	9.45E+08	7.26E+08	2.01E+09	1.33E+09	1.71E+09	7.01E+08	4.07E+09	3.22E+09	2.64E+09
	Test 2	8.33E+08	2.99E+08	3.98E+08	3.16E+09	1.60E+09	1.75E+09	1.79E+09	1.41E+09	2.36E+08	4.14E+09	1.05E+09	2.28E+09
	Mean	**8.44E+08**	**2.24E+08**	**2.94E+08**	**2.05E+09**	**1.16E+09**	**1.88E+09**	**1.56E+09**	**1.56E+09**	**4.68E+08**	**4.11E+09**	**2.14E+09**	**2.46E+09**
fuel2	Test 1	3.81E+09	6.16E+08	3.59E+08	1.39E+09	1.58E+09	6.51E+08	2.06E+09	2.04E+09	1.88E+08	7.24E+09	1.13E+09	3.57E+09
	Test 2	7.84E+08	2.93E+08	4.02E+08	1.69E+09	1.08E+09	1.36E+09	2.69E+09	1.42E+09	2.41E+08	4.99E+09	3.62E+09	3.04E+09
	Mean	**2.29E+09**	**4.55E+08**	**3.81E+08**	**1.54E+09**	**1.33E+09**	**1.01E+09**	**2.38E+09**	**1.73E+09**	**2.15E+08**	**6.12E+09**	**2.37E+09**	**3.31E+09**
fuel3	Test 1	1.06E+09	4.32E+08	2.78E+08	1.27E+09	9.40E+08	5.32E+08	2.21E+09	1.53E+09	3.99E+08	5.40E+09	1.77E+09	2.90E+09
	Test 2	9.78E+08	2.87E+08	1.99E+08	1.38E+09	9.43E+08	1.69E+09	2.11E+09	1.30E+09	2.22E+08	3.15E+09	1.75E+09	2.03E+09
	Mean	**1.02E+09**	**3.59E+08**	**2.39E+08**	**1.33E+09**	**9.41E+08**	**1.11E+09**	**2.16E+09**	**1.41E+09**	**3.11E+08**	**4.27E+09**	**1.76E+09**	**2.46E+09**

		PM (g/km)					**PM (g/km)**						
Fuel	**Test**	**Low**	**Middle**	**High**	**Extra-high**	**WLTC**	**Phase1**	**Phase2**	**Phase3**	**Phase4**	**Phase5**	**Phase6**	**RDE**
E10	Test 1					0.0001							0.0001
	Test 2					0.0001							0.0001
	Mean					**0.0001**							**0.0001**
fuel1	Test 1					0.0000							0.0000
	Test 2					0.0001							0.0001

	Mean					**0.0001**							**0.0001**
fuel2	Test 1					0.0000							0.0000
	Test 2					0.0001							0.0001
	Mean					**0.0001**							**0.0001**
fuel3	Test 1					0.0001							0.0001
	Test 2					0.0001							0.0001
	Mean					**0.0001**							**0.0001**

		HC (g/km)					**HC (g/km)**						
Fuel	**Test**	**Low**	**Middle**	**High**	**Extra-high**	**WLTC**	**Phase1**	**Phase2**	**Phase3**	**Phase4**	**Phase5**	**Phase6**	**RDE**
E10	Test 1	0.137	0.001	0.000	0.000	0.018	0.131	0.001	0.001	0.000	0.003	0.001	0.005
	Test 2	0.120	0.001	0.000	0.001	0.016	0.179	0.002	0.001	0.000	0.002	0.001	0.006
	Mean	**0.129**	**0.001**	**0.000**	**0.000**	**0.017**	**0.155**	**0.002**	**0.001**	**0.000**	**0.003**	**0.001**	**0.005**
fuel1	Test 1	0.083	0.000	0.000	0.000	0.011	0.074	0.001	0.001	0.001	0.001	0.001	0.003
	Test 2	0.118	0.001	0.000	0.000	0.016	0.090	0.001	0.001	0.000	0.001	0.001	0.003
	Mean	**0.101**	**0.001**	**0.000**	**0.000**	**0.013**	**0.082**	**0.001**	**0.001**	**0.000**	**0.001**	**0.001**	**0.003**
fuel2	Test 1	0.101	0.001	0.000	0.000	0.014	0.099	0.001	0.001	0.000	0.001	0.001	0.003
	Test 2	0.085	0.001	0.000	0.000	0.011	0.125	0.001	0.001	0.000	0.001	0.001	0.004
	Mean	**0.093**	**0.001**	**0.000**	**0.000**	**0.012**	**0.112**	**0.001**	**0.001**	**0.000**	**0.001**	**0.001**	**0.004**
fuel3	Test 1	0.080	0.001	0.000	0.000	0.011	0.089	0.001	0.001	0.001	0.001	0.001	0.003
	Test 2	0.076	0.001	0.000	0.000	0.010	0.108	0.001	0.001	0.000	0.001	0.001	0.004
	Mean	**0.078**	**0.001**	**0.000**	**0.000**	**0.010**	**0.099**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.003**

		CO (g/km)					**CO (g/km)**						
Fuel	**Test**	**Low**	**Middle**	**High**	**Extra-high**	**WLTC**	**Phase1**	**Phase2**	**Phase3**	**Phase4**	**Phase5**	**Phase6**	**RDE**
E10	Test 1	0.419	0.017	0.027	0.013	0.072	0.536	0.032	0.013	0.019	0.042	0.019	0.041
	Test 2	0.375	0.017	0.034	0.012	0.068	0.487	0.025	0.014	0.018	0.024	0.018	0.032
	Mean	**0.397**	**0.017**	**0.031**	**0.013**	**0.070**	**0.512**	**0.029**	**0.014**	**0.019**	**0.033**	**0.019**	**0.037**
fuel1	Test 1	1.229	0.017	0.030	0.012	0.179	0.830	0.023	0.013	0.020	0.015	0.018	0.037
	Test 2	1.213	0.017	0.035	0.012	0.178	1.156	0.023	0.017	0.020	0.026	0.018	0.050
	Mean	**1.221**	**0.017**	**0.033**	**0.012**	**0.179**	**0.993**	**0.023**	**0.015**	**0.020**	**0.021**	**0.018**	**0.044**
fuel2	Test 1	1.360	0.017	0.040	0.012	0.199	1.209	0.023	0.013	0.019	0.027	0.018	0.051
	Test 2	0.885	0.017	0.022	0.012	0.132	1.236	0.023	0.013	0.019	0.020	0.018	0.050
	Mean	**1.123**	**0.017**	**0.031**	**0.012**	**0.166**	**1.223**	**0.023**	**0.013**	**0.019**	**0.024**	**0.018**	**0.051**
fuel3	Test 1	1.323	0.017	0.033	0.012	0.192	1.149	0.024	0.013	0.020	0.026	0.017	0.050
	Test 2	1.141	0.016	0.033	0.020	0.171	1.579	0.024	0.013	0.019	0.027	0.018	0.061
	Mean	**1.232**	**0.017**	**0.033**	**0.016**	**0.182**	**1.364**	**0.024**	**0.013**	**0.020**	**0.027**	**0.018**	**0.056**

Engine out

		CO (g/km)					**CO (g/km)**						
Fuel	**Test**	**Low**	**Middle**	**High**	**Extra-high**	**WLTC**	**Phase1**	**Phase2**	**Phase3**	**Phase4**	**Phase5**	**Phase6**	**RDE**
E10	Test 1	7.429	6.060	4.523	4.077	5.062	8.126	8.512	4.953	6.718	4.900	6.550	5.810
	Test 2	6.799	6.096	4.408	3.867	4.876	7.854	7.982	5.411	6.659	4.877	6.565	5.855
	Mean	**7.114**	**6.078**	**4.466**	**3.972**	**4.969**	**7.990**	**8.247**	**5.182**	**6.689**	**4.889**	**6.557**	**5.833**
fuel1	Test 1	7.848	5.880	4.329	3.957	4.976	9.105	8.337	5.611	7.044	4.801	7.233	6.082
	Test 2	7.780	5.963	4.659	4.135	5.150	8.377	8.176	5.410	6.854	4.819	6.998	5.946
	Mean	**7.814**	**5.922**	**4.494**	**4.046**	**5.063**	**8.741**	**8.257**	**5.510**	**6.949**	**4.810**	**7.116**	**6.014**
fuel2	Test 1	8.238	6.608	4.668	4.152	5.349	8.436	8.022	5.290	6.468	4.891	6.936	5.880
	Test 2	7.785	6.385	4.615	4.028	5.185	8.911	8.525	5.075	6.402	4.763	5.611	5.656
	Mean	**8.011**	**6.497**	**4.642**	**4.090**	**5.267**	**8.674**	**8.274**	**5.182**	**6.435**	**4.827**	**6.273**	**5.768**
fuel3	Test 1	7.817	6.390	4.553	4.079	5.189	8.687	8.184	5.263	6.861	4.905	6.760	5.914
	Test 2	7.766	6.387	4.921	4.362	5.397	9.576	7.735	5.561	6.878	4.930	7.079	6.021
	Mean	**7.791**	**6.388**	**4.737**	**4.220**	**5.293**	**9.132**	**7.959**	**5.412**	**6.869**	**4.917**	**6.919**	**5.968**

Unregulated pollutants

		NH3 (mg/km)					NH3 (mg/km)						
Fuel	**Test**	**Low**	**Middle**	**High**	**Extra-high**	**WLTC**	**Phase1**	**Phase2**	**Phase3**	**Phase4**	**Phase5**	**Phase6**	**RDE**
E10	Test 1	1.494	1.193	1.331	0.645	1.080	14.294	3.216	0.273	0.201	1.228	0.254	1.311
	Test 2	0.879	0.611	0.912	0.497	0.699	13.628	2.952	0.320	0.212	0.502	0.213	1.011
	Mean	**1.186**	**0.902**	**1.122**	**0.571**	**0.889**	**13.961**	**3.084**	**0.296**	**0.207**	**0.865**	**0.234**	**2.681**
fuel1	Test 1	5.638	1.558	1.119	0.645	1.634	13.594	2.686	0.307	0.236	0.276	0.192	0.893
	Test 2	1.459	1.560	1.109	0.573	1.057	14.944	2.791	0.322	0.202	0.423	0.200	0.994
	Mean	**3.549**	**1.559**	**1.114**	**0.609**	**1.346**	**14.269**	**2.738**	**0.315**	**0.219**	**0.349**	**0.196**	**2.662**
fuel2	Test 1	6.175	1.924	1.240	0.604	1.802	22.714	3.322	0.336	0.239	0.376	0.230	1.254
	Test 2	1.003	0.758	0.584	0.377	0.601	33.204	3.759	0.293	0.179	0.310	0.138	1.520
	Mean	**3.589**	**1.341**	**0.912**	**0.491**	**1.202**	**27.959**	**3.540**	**0.314**	**0.209**	**0.343**	**0.184**	**4.671**
fuel3	Test 1	12.805	2.009	0.897	0.466	2.543	33.071	4.562	0.340	0.103	0.000	0.000	1.487
	Test 2	2.584	2.038	1.480	0.707	1.465	37.465	4.115	0.311	0.191	0.616	0.186	1.797
	Mean	**7.695**	**2.023**	**1.189**	**0.587**	**2.004**	**35.268**	**4.339**	**0.326**	**0.147**	**0.308**	**0.093**	**5.803**

		Formaldehyde (mg/km)					Formaldehyde (mg/km)						
Fuel	**Test**	**Low**	**Middle**	**High**	**Extra-high**	**WLTC**	**Phase1**	**Phase2**	**Phase3**	**Phase4**	**Phase5**	**Phase6**	**RDE**
E10	Test 1	1.501	0.231	0.169	0.112	0.338	0.883	0.141	0.062	0.088	0.098	0.083	0.111
	Test 2	0.959	0.033	0.014	0.023	0.146	1.090	0.031	0.020	0.019	0.015	0.020	0.047
	Mean	**1.230**	**0.132**	**0.091**	**0.068**	**0.242**	**0.987**	**0.086**	**0.041**	**0.054**	**0.057**	**0.051**	**0.079**
fuel1	Test 1	0.451	0.034	0.029	0.030	0.086	0.354	0.070	0.039	0.043	0.038	0.034	0.050
	Test 2	0.828	0.112	0.071	0.078	0.182	0.306	0.037	0.019	0.025	0.025	0.019	0.031
	Mean	**0.640**	**0.073**	**0.050**	**0.054**	**0.134**	**0.330**	**0.054**	**0.029**	**0.034**	**0.031**	**0.027**	**0.041**
fuel2	Test 1	0.726	0.204	0.112	0.155	0.227	0.666	0.207	0.129	0.153	0.157	0.129	0.164
	Test 2	0.764	0.208	0.100	0.150	0.227	0.673	0.199	0.097	0.100	0.124	0.115	0.136
	Mean	**0.745**	**0.206**	**0.106**	**0.152**	**0.227**	**0.669**	**0.203**	**0.113**	**0.126**	**0.140**	**0.122**	**0.150**
fuel3	Test 1	0.501	0.109	0.070	0.079	0.138	0.197	0.049	0.029	0.015	0.000	0.000	0.020
	Test 2	0.433	0.053	0.038	0.000	0.095	0.476	0.135	0.055	0.092	0.085	0.084	0.093
	Mean	**0.467**	**0.081**	**0.054**	**0.040**	**0.117**	**0.337**	**0.092**	**0.042**	**0.053**	**0.042**	**0.042**	**0.057**

		Acetaldehyde (mg/km)					Acetaldehyde (mg/km)						
Fuel	**Test**	**Low**	**Middle**	**High**	**Extra-high**	**WLTC**	**Phase1**	**Phase2**	**Phase3**	**Phase4**	**Phase5**	**Phase6**	**RDE**
E10	Test 1	3.248	0.549	0.550	0.541	0.903	4.250	1.178	0.684	0.912	1.046	0.746	0.992
	Test 2	2.678	0.080	0.096	0.159	0.456	4.111	0.013	0.002	0.006	0.041	0.050	0.131
	Mean	**2.963**	**0.314**	**0.323**	**0.350**	**0.680**	**4.180**	**0.596**	**0.343**	**0.459**	**0.544**	**0.398**	**0.562**
fuel1	Test 1	0.202	0.071	0.123	0.158	0.135	0.974	0.662	0.397	0.415	0.420	0.208	0.426
	Test 2	0.923	0.419	0.573	0.730	0.643	0.745	0.542	0.300	0.415	0.449	0.348	0.410
	Mean	**0.562**	**0.245**	**0.348**	**0.444**	**0.389**	**0.859**	**0.602**	**0.348**	**0.415**	**0.435**	**0.278**	**0.418**
fuel2	Test 1	0.345	0.016	0.031	0.026	0.068	0.699	0.030	0.009	0.018	0.024	0.001	0.035
	Test 2	0.797	0.404	0.410	0.487	0.487	1.623	0.791	0.377	0.132	0.076	0.166	0.298
	Mean	**0.571**	**0.210**	**0.221**	**0.256**	**0.277**	**1.161**	**0.410**	**0.193**	**0.075**	**0.050**	**0.083**	**0.166**
fuel3	Test 1	1.804	0.741	0.511	0.471	0.715	2.331	1.184	0.850	0.276	0.000	0.000	0.454
	Test 2	1.943	0.912	0.916	0.000	1.136	1.512	0.427	0.227	0.025	0.145	0.315	0.249
	Mean	**1.873**	**0.827**	**0.714**	**0.236**	**0.925**	**1.921**	**0.806**	**0.539**	**0.151**	**0.073**	**0.157**	**0.351**

		PN10 (#/km)					PN10 (#/km)						
Fuel	**Test**	**Low**	**Middle**	**High**	**Extra-high**	**WLTC**	**Phase1**	**Phase2**	**Phase3**	**Phase4**	**Phase5**	**Phase6**	**RDE**
E10	Test 1	4.30E+11	1.42E+09	1.35E+09	1.55E+09	1.12E+11	3.39E+11	2.47E+10	1.38E+10	1.09E+10	3.89E+10	1.13E+10	3.20E+10
	Test 2	3.61E+11	3.81E+09	3.95E+09	4.45E+09	6.30E+10	7.34E+11	3.99E+10	2.00E+10	9.63E+09	5.15E+10	1.15E+10	5.04E+10
	Mean	**3.95E+11**	**2.62E+09**	**2.65E+09**	**3.00E+09**	**8.77E+10**	**5.36E+11**	**3.23E+10**	**1.69E+10**	**1.03E+10**	**4.52E+10**	**1.14E+10**	**4.12E+10**
fuel1	Test 1	1.73E+09	5.63E+08	5.14E+08	2.39E+09	1.62E+09	6.51E+09	3.30E+09	3.94E+09	1.53E+09	9.16E+09	6.55E+09	5.94E+09

	Test 2	1.80E+09	8.19E+08	8.45E+08	6.81E+09	3.36E+09	4.46E+09	3.92E+09	3.41E+09	9.24E+08	9.39E+09	3.08E+09	5.36E+09
	Mean	**1.76E+09**	**6.91E+08**	**6.80E+08**	**4.60E+09**	**2.49E+09**	**5.49E+09**	**3.61E+09**	**3.67E+09**	**1.23E+09**	**9.27E+09**	**4.82E+09**	**5.65E+09**
fuel2	Test 1	7.78E+09	1.43E+09	9.21E+08	3.36E+09	3.49E+09	1.93E+09	5.37E+09	5.42E+09	7.33E+08	1.69E+10	2.79E+09	8.65E+09
	Test 2	1.80E+09	7.61E+08	8.38E+08	3.84E+09	2.31E+09	3.92E+09	6.33E+09	3.70E+09	8.36E+08	1.15E+10	6.50E+09	6.94E+09
	Mean	**4.79E+09**	**1.10E+09**	**8.80E+08**	**3.60E+09**	**2.90E+09**	**2.93E+09**	**5.85E+09**	**4.56E+09**	**7.84E+08**	**1.42E+10**	**4.64E+09**	**7.80E+09**
fuel3	Test 1	2.61E+09	1.06E+09	7.14E+08	3.04E+09	2.17E+09	1.71E+09	4.78E+09	3.48E+09	1.20E+09	1.19E+10	3.89E+09	6.45E+09
	Test 2	2.46E+09	9.40E+08	6.66E+08	3.47E+09	2.24E+09	3.72E+09	5.08E+09	3.20E+09	7.02E+08	7.93E+09	4.32E+09	5.05E+09
	Mean	**2.54E+09**	**1.00E+09**	**6.90E+08**	**3.26E+09**	**2.20E+09**	**2.71E+09**	**4.93E+09**	**3.34E+09**	**9.49E+08**	**9.92E+09**	**4.10E+09**	**5.75E+09**

Engine out

		PN10 (#/km)					**PN10 (#/km)**						
Fuel	**Test**	**Low**	**Middle**	**High**	**Extra-high**	**WLTC**	**Phase1**	**Phase2**	**Phase3**	**Phase4**	**Phase5**	**Phase6**	**RDE**
E10	Test 1	1.91E+12	2.39E+11	1.37E+11	5.87E+11	5.53E+11	6.89E+11	8.73E+11	4.26E+11	3.54E+11	1.75E+12	2.78E+11	9.32E+11
	Test 2	6.89E+11	8.73E+11	4.26E+11	3.54E+11	9.32E+11	2.76E+12	1.07E+12	5.96E+11	4.97E+11	2.16E+12	4.06E+11	1.23E+12
	Mean	**1.30E+12**	**5.56E+11**	**2.81E+11**	**4.70E+11**	**7.42E+11**	**1.73E+12**	**9.69E+11**	**5.11E+11**	**4.25E+11**	**1.96E+12**	**3.42E+11**	**1.08E+12**
fuel1	Test 1	7.30E+10	4.63E+10	4.27E+10	1.66E+11	9.13E+10	9.13E+10	1.10E+11	2.11E+11	7.68E+10	3.44E+11	1.37E+11	2.21E+11
	Test 2	9.76E+10	6.75E+10	5.62E+10	1.95E+11	1.13E+11	1.02E+11	2.08E+11	1.29E+11	7.39E+10	5.30E+11	2.33E+11	2.90E+11
	Mean	**8.53E+10**	**5.69E+10**	**4.94E+10**	**1.80E+11**	**1.02E+11**	**9.65E+10**	**1.59E+11**	**1.70E+11**	**7.53E+10**	**4.37E+11**	**1.85E+11**	**2.56E+11**
fuel2	Test 1	1.51E+12	6.80E+10	6.44E+10	8.28E+10	2.62E+11	7.77E+10	2.24E+11	3.37E+11	7.86E+10	4.15E+11	1.98E+11	3.02E+11
	Test 2	1.18E+11	9.01E+10	6.70E+10	1.44E+11	1.06E+11	1.32E+11	2.67E+11	2.70E+11	1.46E+11	5.48E+11	9.99E+10	3.30E+11
	Mean	**8.14E+11**	**7.91E+10**	**6.57E+10**	**1.13E+11**	**1.84E+11**	**1.05E+11**	**2.45E+11**	**3.03E+11**	**1.12E+11**	**4.81E+11**	**1.49E+11**	**3.16E+11**
fuel3	Test 1	1.84E+11	7.30E+10	6.78E+10	8.42E+10	9.00E+10	1.11E+11	1.53E+11	1.15E+11	1.30E+11	4.81E+11	1.14E+11	2.51E+11
	Test 2	1.60E+11	7.47E+10	7.56E+10	9.57E+10	9.37E+10	1.25E+11	2.10E+11	1.86E+11	8.31E+10	3.99E+11	1.06E+11	2.43E+11
	Mean	**1.72E+11**	**7.39E+10**	**7.17E+10**	**8.99E+10**	**9.19E+10**	**1.18E+11**	**1.81E+11**	**1.51E+11**	**1.06E+11**	**4.40E+11**	**1.10E+11**	**2.47E+11**

Glossary

CH_4 – Methane, greenhouse gas, GWP of 30
CO – Carbon monoxide
CO_2 – Carbon dioxide
CVS – Constant Volume Sampling
DVPE – Dry Vapour Pressure Equivalent
GDI – Gasoline Direct Injection
GPF – Gasoline Particulate Filter
GWP- The Global Warming Potential of a gas is the mass of CO_2 that would produce an equivalent impact on the greenhouse effect.
LHV – Low Heating Value
MCT – Mercury Cadmium Telluride
MDC – Minimum Detectable Concentration
MV - Measured value
N_2O – Nitrous oxide - greenhouse gas, GWP 298
NMHC – Mass of non-methane hydrocarbons
NO – Nitrogen monoxide
NO_2 – Nitrogen dioxide
NO_x – Nitrogen oxides
NRP – Non-regulated pollutants
PM – Particle Mass
PN – Particle Number
RDE – Real Driving Emissions
(T)HC – Total mass of hydrocarbons
TWC – Three Way Catalyst