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Tittle:

Analysis of pollutant emissions and fuel consumption, during real driving cycles in different intake temperature scenarios.

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ABSTRACT

Current European vehicle homologation regulations are increasingly restrictive. Recently, World-wide light-duty test cycle (WLTC) and Real driving emissions (RDE) cycles have been introduced as type approval tests for new vehicles.

This document studies the effect of intake temperature on pollutant emissions and fuel consumption of a Euro 6 Diesel engine when tested under WLTC and RDE.

The tests have been performed by setting the temperature at the outlet of the water charge air cooler (WCAC) at 35ºC and 20ºC in different tests. To do that, the air-cooler was

immersed in a temperature-controlled water bath. This temperature reduction can be produced due to an improvement in the WCAC in the same ambient temperature or also with the same WCAC in case of the ambient temperature is lower.

All tests have been carried out in an engine test bench, eliminating the uncertainty involved on the road (driving mode, traffic, ambient temperature, etc..).

Once the WLTC and RDE cycles were performed, carbon dioxide (CO_2) and pollutant results were analysed. Nitrogen oxides (NO_X) emissions were considerably reduced when the engine intake temperature air was decreased, concretely a 7.1% in RDE and 11.63% in WLTC and the CO_2 emissions were also cut down around 1%.

Abbreviations

- CO = Carbon Monoxide.
- CO_2 = Carbon Dioxide.
- DOC = Diesel oxidation catalyst.
- DPF = Diesel particulate filter.
- EGR = Exhaust gas recirculation.
- HCNM = Non-methane Hydrocarbons.
- NEDC = New European Driving Cycle.
- NO_X = Nitrogen oxides.
- PEMS = Portable emissions measurement system.

- PM=Particles mass.
- RDE=Real Driving Emissions.
- SCR = Selective catalytic reduction.
- THC = Total Hydrocarbons.
- WCAC= Water charge air cooler.
- WLTC= Worldwide Light-duty Test Cycle.

1. INTRODUCTION

Nowadays, many of the largest cities have implanted different regulations, especially to ban the circulation of older vehicles, and reduce, as much as possible pollutant emissions. These restrictions were applied due to poor air quality, as reported in 2019 by the European Environment Agency (EEA) [1]. The 2020 report [2] points to significant reductions in emissions of air pollutants, particularly from road transport, aviation and international shipping but largely due to the lockdown actions introduced by most of the European countries to reduce transmission of COVID-19. The EEA considers air quality through the parameter known as air quality index (AQI) [3]. To calculate this parameter, it is necessary to consider the hourly concentrations of the polluting substances as ozone (O_3), particulate matter (PM), carbon monoxide (CO), sulphur dioxide (SO_2), and nitrogen dioxide (NO_2).

In the last few years, cars have been strongly blamed, mainly vehicles equipped with diesel engines, and particularly the older ones, as they produce large quantities of PM and NOx, since the regulation was not so demanding with laxer type approval emissions.

These type approval emissions have been reduced until 6.25 times in ten years, but real driving emissions have only decreased an 40% on average between Euro3 and Euro6 [4]. In other words, real driving emissions were up to 4 to 10 times greater than the type approval limits, depending on the source [5].

But according to EEA [6] road transport is not the main and only responsible for air pollution, with a contribution of 28.12% of NO_X, 17.97% of CO, 0.11% of SO_X and 2.88% and 3.59% of particle matter smaller than 10 and 2.5µm respectively. Furthermore, as also stated by EEA source [6], air pollutant emissions trends from transport are constantly downward.

This reduction is attributable to anti-pollution regulations which have taken place during the last years. Nowadays, car manufacturers efforts are principally focused on decrease pollutant emission in the design of new vehicles, and certainly NO_X emission reduction implies the main challenge for them [7] and to type approve vehicles according to regulation a large number of methods to reduce emissions are used [8].

In 1946, the Russian physicist Yakov Borisovich Zeldovich [9] postulated the thermal mechanism of NO_X generation, showing that it has a strong temperature dependence [10]. Chemical reactions found in Eq. 1, 2 and 3 describe the extended Zeldovich mechanism.

$$N_2 + O \rightarrow NO + N \qquad [1]$$

$$N + O_2 \rightarrow NO + O \qquad [2]$$

$$N + OH \rightarrow NO + H \qquad [3]$$

The above-mentioned reactions are highly affected by the combustion temperature, so the nitrogen oxide (NO) production increases as this temperature increases. There are other mechanisms although they have more limited impact. Some examples are the prompt mechanism by Fenimore [11], the Nitrous Oxide (N_2O) intermediate mechanism [12] [13], or the fuel contribution mechanism mainly governed by fuel richness [10] [12] [13].

According to the EEA [14], most of atmospheric NO_2 is emitted in form of NO, and later on it is rapidly oxidized becoming NO_2 when it reacts with the atmospheric oxygen. NO_2 in presence of hydrocarbons and ultraviolet light is the main tropospheric ozone and nitrates aerosol source. Furthermore, both substances present in ambient, represent a significant fraction of mass particles with diameter less than 2.5 micrometres known as $PM_{2.5}$. People exposed to tropospheric ozone can suffer from respiratory symptoms, airway inflammation, to lung cancer [15].

In addition, NO_X interacts with water, oxygen and other chemicals in the atmosphere generating acid rain [16], which can harm sensitive ecosystems such as lakes and forests. Other possible effect is produced by nitrate particles that result from NO_X and make hazy air and difficult to see through.

To check if pollutant emissions were under the type approval thresholds stablished by regulation, the vehicle had to be tested with a new European driving cycle (NEDC) (until Euro 6 Temp regulation). But later on, this cycle became out of date due to the low acceleration settings when compared with the performance of current engines. [17]

Consequently, the European Commission stablished relevant modifications about engine pollutants validation. Two new cycles were implanted, WLTC and RDE appeared for the first time in 2016 [18].

Besides this, there is the problem of greenhouse gas emissions culprits of climate change. This type of emissions has no boundaries. In other words, greenhouse gases emitted in any part of the world affect the entire planet. Internal combustion engines that work with fossil or hydrocarbons fuels, during the combustion, emit CO_2 gases as Eq. 4 shows. In sum, more fuel consumption involves more CO_2 emissions.

$$C_nH_{2n+2} + O_2 \rightarrow CO_2 + H_2O \qquad [4]$$

CO_2 emission comes from total transport representing a 24% in 2019 according to the International Energy Agency (IEA) [19], and road vehicles like cars, trucks, buses and two- and three-wheelers contribute to nearly three-quarters of transport CO_2 emissions, which involves around a 18% of the total CO_2 emissions.

The well-known trade-off between NOx and CO_2 emissions represent an important inconvenient when using different pollutant emissions control as EGR systems what impairs the combustion process or aftertreatment systems, increasing engine back pressure, and subsequently pumping losses.

Nowadays, car manufacturers have made their utmost efforts to reduce pollutant emission and improve the engines performance. Being quite complex to fulfil both purposes, since many times the improvement of one leads to the worsening of the other.

All the spark ignition engine pollutant emissions can be reduced with a unique device as is the three-way catalytic converter. However, the issue in diesel engines is harder to solve. In this kind of engines, THC and CO emissions can be reduced at the diesel oxidation catalyst, commonly used in this kind of engines. Particulates can as well be reduced through combustion systems improvement mainly with sophisticated injection systems, in addition diesel engines are equipped with particulate filters.

Nevertheless, NO_x emissions are a hard problem to solve. Although EGR systems are fully implemented in diesel engines reducing significantly NO_X emissions at the combustion chamber, exhaust NO_X emissions are still important. Two different technologies, Lean NO_x Trap (LNT) and Selective Catalyst Reduction (SCR), are currently used to further reduce NO_X emissions.

For a given technology, pollutant emissions are also influenced by the ambient conditions. As mentioned above, combustion temperature directly influences the production of NO_X. Among other parameters, combustion temperature is influenced by the intake temperature. As a consequence, it is expected that the emissions of the engines will also be different when operating under different temperature conditions. Given that the regulation allows the type-approval tests to be carried out in a wide ambient temperature range, as will be indicated later, the final emission values collected from the same engine and route may differ considerably if the ambient temperatures where the tests are carried out are different.

Along with the direct effect of temperature on emissions, engines can automatically modify calibration conditions, in such a way that these modifications can also affect the pollutant emissions. The aim of this work is to study the influence of intake manifold temperature on pollutant emissions in a diesel engine under RDE and WLTC conditions. It may be due to an improvement in the efficiency of the WCAC, or a different ambient temperature. Four different tests were carried out: two WLTC and two RDE cycles having two water charge air cooler (WCAC) outlet temperature (T2'), setpoints at 20º and 35º Celsius. All the tests have been carried out into a test bench able to reproduce driving conditions. The moderate range of selected temperatures of the tests prevents the engine from changing the calibration (using different engine maps control) and so the effect of changing T2' can be studied under the standard control strategies in all tests that have been performed.

Four tests will be analysed, focusing on pollutant emissions. Pollutant substances evaluated will be the THC, NO_X, CO, and the CO_2 emissions strongly linked to the fuel consumption.

2. WLTC AND RDE

WLTC was defined by the European regulation, 1151/2017 [20] and stablished the instantaneous vehicle speed to reproduce the cycle. The four phases of the WLTC, low, medium, high and extra-high, are defined in the XXI annex of the regulation. Gear shifting procedures are also described to apply in vehicles equipped with manual shift transmissions. The gear engaged is based on the balance between the power provided by the engine in all possible gears at a specific cycle phase and the required power. The WLTC characteristics are shown in table 1.

RDE cycle appeared in March 2016 as a type-approval test in the 427/2016 regulation [18], but later on the European Commission made some changes to make a more consistent cycle. The 1151/2017 regulation [21] and, 1832/2018 regulation [22] determine these changes. Following the regulations, the trip sequence must be based on urban driving followed by rural and motorway phases. Urban phase is characterised by vehicle speeds lower than or equal to 60 km/h, rural by vehicle speeds higher than 60 and lower than or equal to 90 km/h and motorway by speeds above 90 km/h. RDE cycles can have countless possibilities and different characteristics, within valid cycles, but it is also possible to perform a cycle on road, which finally turns out to not being approvable. In fact, there are studies to help to build a cycle for real driving emissions that can fulfil the regulation requirements [22].

RDE test cycle in this paper was mainly obtained from a specific cycle performed on road [23], but it had to be slightly modified to fulfil with the newest regulation. After that, conditions of the cycle have been reproduced in a test bench to eliminate the variations that many parameters as the weather, ambient pressure [24],[25] , traffic, driver behaviour that produces different dynamic solicitations [26] , road grade [27], aftertreatment status or vehicle mileage can produce [28],[29],[30],[31],[32],[33],[34] as well as other issues that can appear which can spoil the test like DPF regeneration, traffic jams, etc. For example, different on road cycles that follow the same route, can have a high NOx emission dispersion [35], and it is likely to find emissions differences of up to 24% [36]. In addition, portable emission measurement systems (PEMS) have worse accuracy than a stationary laboratory equipment [37]. These uncertainties would make harder the analysis differences between tests, masking any improvement that may occur due to the change in intake temperature. However, even reproducing RDE cycles under controlled conditions in a test bench can imply a big challenge [38], this is the most reliable way.

Table 1 shows the characteristic of both WLTC and RDE tests performed in this study.

		WLTC	RDE
Duration	min	30	94.88
Distance	km	23.15	69.51
Average speed	km/h	46.50	43.95
Max. Speed	km/h	131.30	131.00
Idle proportion	%	13.06%	29%
Ambient temperature	ºC	23	23
Ambient pressure	Pa	100845	100845

Table 1: WLTC and RDE characteristics.

Fig. 1 shows instantaneous vehicle speed (left axis) and gear engage (right axis), for both WLTC and the specific RDE, and each of the phases in which they are divided.

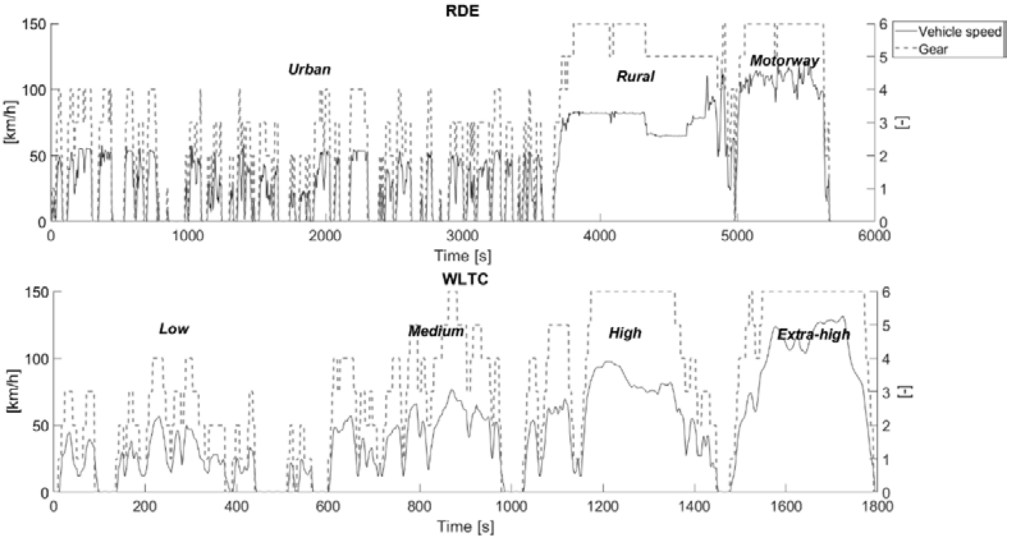

Figure 1: WLTC and RDE cycles

Current RDE regulation [21] stablishes that the test shall be conducted within a specified ambient temperature range. Moderate temperature conditions have been set when the ambient temperature is greater than or equal to 0 °C and lower than or equal to 30 °C. Extended temperature conditions are considered for temperatures between -7ºC and 0ºC and from 30ºC to 35ºC. This wide temperature range can lead to large differences in fuel consumption and emissions, as studies already carried out in NEDC and WLTC cycles show [39]. Extended conditions also can be reached through altitude, when it is higher than 700 meters and lower or equal to 1300 meters above sea level. If some part of the RDE cycle or the entire test is performed outside of normal or extended conditions, the test is not considered as valid. During a particular phase of the cycle, if temperature, altitude or both enter in extended conditions, pollutant emissions have to be divided by 1.6 during this determined interval, except for CO_2 emissions.

However, in the case of WLTC, the applicable regulation [20] dictates that the laboratory atmospheric temperature should be regulated at a set point of 23 °C and cannot be deviated by more than ± 5 °C.

The different temperatures that have been chosen for performing the cycles could represent WLTC an RDE tests with different air cooler efficiencies that is fitted in the vehicle. In the case of the RDE, it also could be produced due to different ambient temperatures which could further change WCAC outlet temperature.

3. MATERIALS AND METHODS

3.1. Simulated vehicle

The vehicle simulated in the test cell is a C-segment passenger car. This type of vehicle is the second segment sold in 2020 with a market share of 16,97% [40], so it represents a considerable part of the European fleet. To perform the simulation, car and gear box characteristics are needed to be implanted in the simulation software. Table 2 shows the main vehicle characteristics.

Characteristics		
Tyres code		195/60 R16
Vehicle mass	*kg*	1581
Frontal Area	m^2	2.8
Drag coefficient (Cx)		0.3
Nº of gears:		6
1st	*Vehicle speed (km/h at 1000 rpm)*	8.69
2nd		16.42
3rd		25.42
4th		37.77
5th		48.79
6st		57.32

Table 2: Vehicle Characteristics.

Representative engine characteristics are listed in the table 3:

Engine Characteristics		
Fuel		Diesel
Aspiration		Turbocharged
Engine capacity	*cm³*	1598
Nº of cylinders/bore/stroke		4/80mm/79.5mm
Max. Power	*kW/rpm*	96/4000
Max. Torque	*Nm/rpm*	320/1750-2500
Aftertreatment system		DPF/DOC

Table 3: Engine characteristics.

This engine was developed under the course of Euro 5 regulation, when pollutant limits were verified using the NEDC cycle. It has the particularity of being equipped with two exhaust gas recirculation (EGR) systems: high-pressure and low-pressure loop. During the engine warming up, the high-pressure EGR strategy is used. Engine electronic control unit switches towards Low-pressure EGR as a function of coolant and ambient temperatures.

The engine is also equipped with two aftertreatment systems: DPF (Diesel Particulate Filter) and DOC (Diesel Oxidation Catalyst). Thanks to EGR, DPF and DOC, this engine fulfils the EURO 5 requirements.

3.2. Engine test cell

The test cell to host the engine is equipped with measurement and safety systems. The main systems are listed below:

- **Electromagnetic brake:** It simulates the real driving conditions. It is liable to do the resistance force and to maintain the requested engine speed at each moment. This resistance force considers aerodynamic, road friction, and inertia forces.
- **Pollutant emission meter:** The dispositive Horiba Mexa-7000 has been used to measures the volumetric concentrations of O_2, HC, NO_X, CO_2 and CO at the tail pipe. CO_2 concentration is also registered in the inlet manifold. EGR quantity is estimated thanks to this measure. Measuring principles, ranges and uncertainties for each one of the substances are listed in table 4. The Uncertaintiy-1 is expressed in relative values while Uncertainty-2 shows absolute values.

Pollutant	Measuring principle	Range-1	Uncertainty-1	Range-2	Uncertainty-2
CO	NID	0-1250ppm	2%	1250-5kppm	25ppm
CO_2	NID	0-10%	2%	10%-20%	0.2vol%
NO_X	HCLD	0-250ppm	2%	250-5kppm	5ppm
THC	HFID	0-250ppm	2%	0-50kppm	5ppm

Table 4: Pollutant emissions measuring principles, ranges and uncertainties of Horiba Mexa-7000. NID: Nondispersive Infrared Detector; HCLD: Heated Chemiluminescent Detector; HFID: Heated Flame Ionization Detector.

From polluting volumetric concentrations of NO_X, THC and CO, the mass flow emissions have been calculated using the equation 5.

$$Pollutant\left[\frac{g}{s}\right] = \frac{MM_{pollutant}}{MM_{air}} * \frac{Pollutant[ppm]*kw}{10000} * (AMF + FMF)\left[\frac{g}{s}\right] \qquad [5]$$

- MM= Molecular mass.
- Pollutant= Dry volumetric concentration measured by the pollutant emissions analyser.
- kw= Wet-dry correction factor. In case of THC, dry-wet correction is equal to 1 since the analyser measures them in wet conditions.
- AMF= Air mass flow.
- FMF=Fuel mass flow.

And in the case of CO_2, mass flow emissions are calculated by means of the equation 6:

$$CO_2\left[\frac{g}{s}\right] = \frac{MM_{CO_2}}{MM_{air}} * CO_2[\%] * kw * (AMF + FMF)\left[\frac{g}{s}\right] \qquad [6]$$

- **Cooling system:** To control the intake temperature, the charge-cooler is submerged in a coolant tank. A PID controller regulates the coolant flow in order to keep the required air temperature.

Fig. 2 shows the test bench layout.

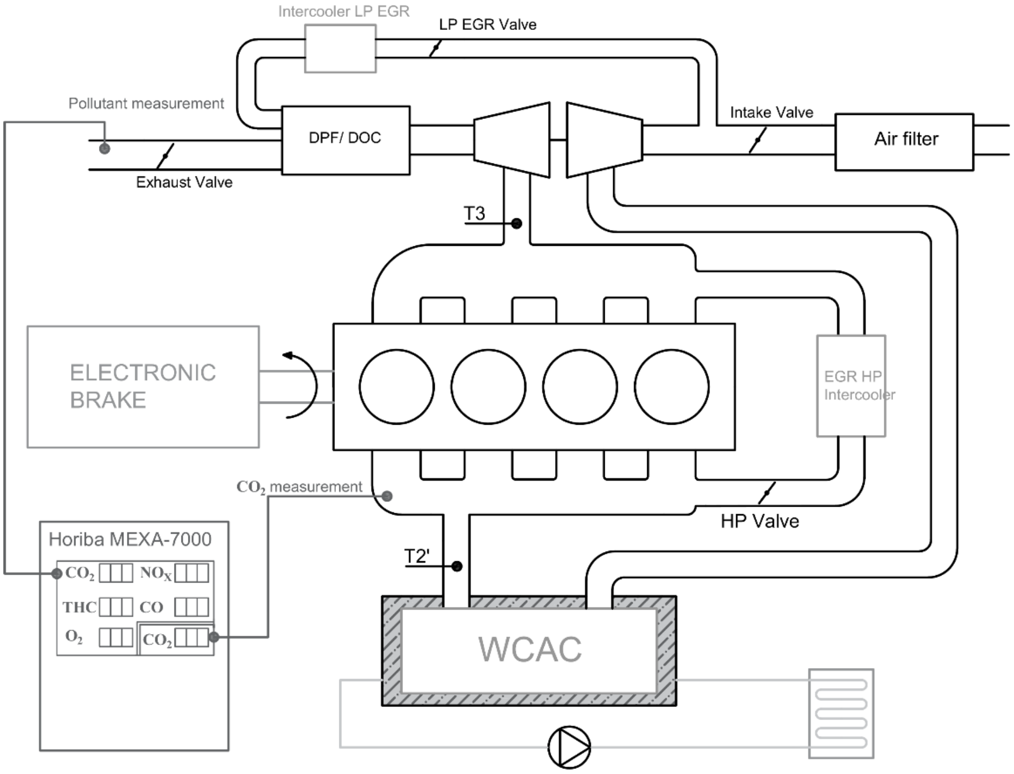

Figure 2: Engine test cell layout.

4. RESULTS

A great amount of data was collected during the test in continuous mode. The acquisition time was 1 Hz as RDE regulation requires. Temperatures, pressures, mass fuel flows and pollutant concentrations in addition to torque, and engine speed were measured.

Even though T2’ is regulated in each test by a PID controller, considering the significant transient conditions of both RDE and WLTC tests, which produces a different intake temperature conditions (variation of EGR rates, AMF and outlet compressor temperature), it is not possible to accurately match the temperature setpoint as Fig. 2 shows. The high thermal inertia of the coolant tank together with physic WCAC characteristics hinders to have a T2’ precise regulation. In any case, the change of intake temperature for the different tests are significant (20ºC or 35ºC), reducing the effect of small variations on the global conclusions and T2’ data represents realistic conditions. Fig. 3 presents T2’ and exhaust manifold temperature (T3), showing in the right-hand the WLTC data and in the left-hand the data corresponding to the RDE cycle.

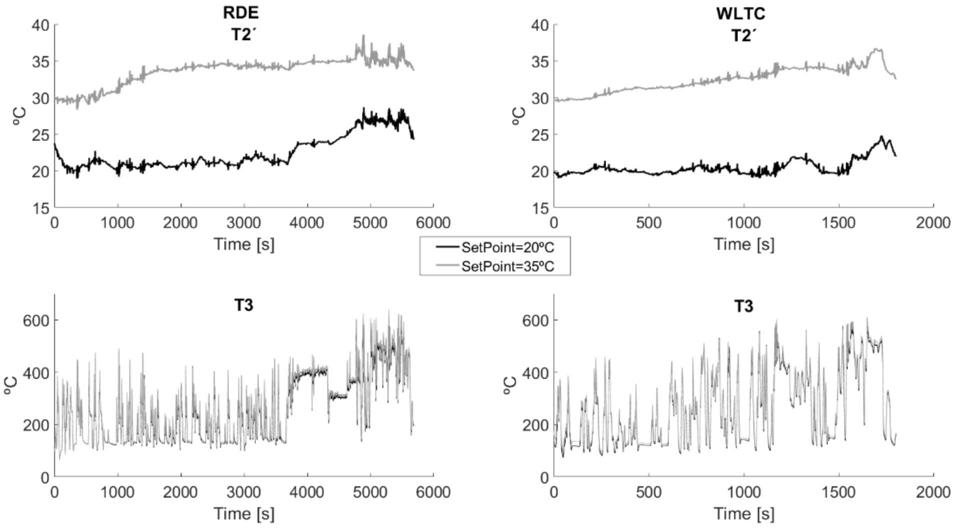

Figure 3: T2’ and T3.

The first consequence of lowing the intake temperature is an air density increase. It entails a better breathing capacity of the engine which once the desired AMF stipulated by the engine control unit (ECU), is reached, makes possible to increase the EGR mass flow quantity, and more EGR means less NO_X emissions.

A lower combustion temperature also helps to prevent NO_X emissions. The T3 (that is related with the combustion temperature) is also shown in fig. 3. Although great variations are not clearly noticed in fig.3, table 5 and 6 presents the average temperatures for the four tests by zones, where these differences can be noticed.

	T2'_avg _35ºC	**T2'_avg _20ºC**	**Abs. Difference**	**T3_avg _35ºC**	**T3_avg _20ºC**	**Abs. Difference**
Urban	30.84ºC	20.99ºC	-9.85ºC	195.15ºC	189.05ºC	-6.10ºC
Rural	34.94ºC	24.29ºC	-10.65ºC	363.27ºC	351.18ºC	-12.10ºC
Motorway	35.06ºC	26.68ºC	-8.38ºC	456.54ºC	443.06ºC	-13.49ºC
Total	32.32ºC	22.47ºC	-9.85ºC	266.95ºC	258.52ºC	-8.42ºC

Table 5: RDE T2'and T3

	T2'_avg _35ºC	**T2'_avg _20ºC**	**Abs. Difference**	**T3_avg _35ºC**	**T3_avg _20ºC**	**Abs. Difference**
Low	30.55ºC	19.88ºC	-10.67ºC	182.06ºC	171.83ºC	-10.23ºC
Medium	32.12ºC	20.12ºC	-12.00ºC	258.72ºC	253.74ºC	-4.98ºC
High	33.72ºC	20.47ºC	-13.26ºC	313.90ºC	306.15ºC	-7.75ºC
Extra-high	34.50ºC	22.05ºC	-12.46ºC	396.02ºC	384.95ºC	-11.07ºC
Total	32.43ºC	20.48ºC	-11.95ºC	271.93ºC	263.42ºC	-8.51ºC

Table 6: WLTC T2' and T3.

Fig. 4 represents the instantaneous and accumulated emissions using solid and dashed lines in left and right axis respectively for the two cycles under study.

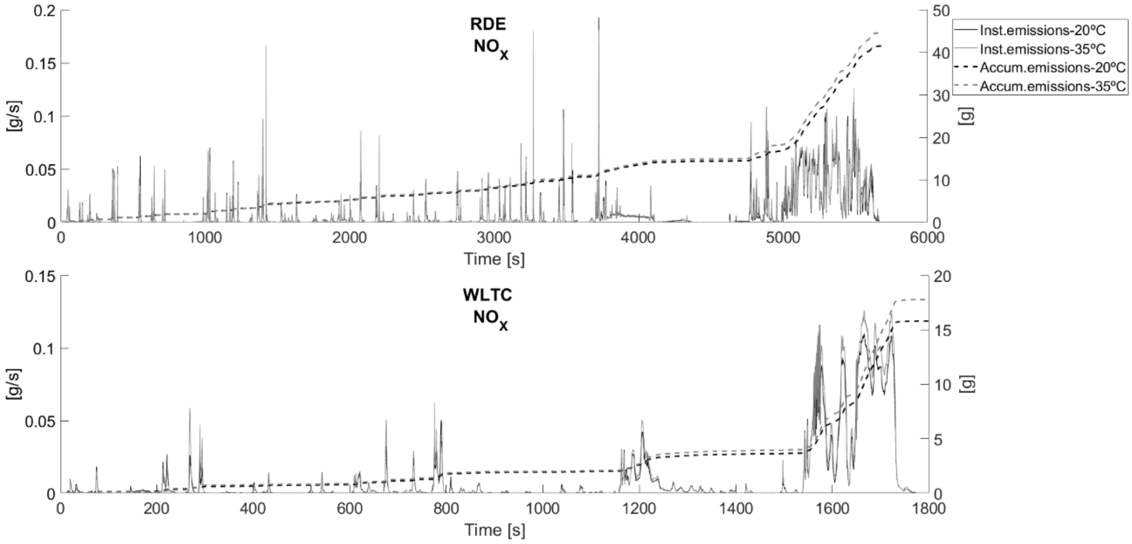

Figure 4: Instantaneous and accumulated NO_X emissions.

In fig. 4, the differences between instantaneous NO_X emissions are not easy to notice however, focusing on accumulated emissions, differences are evident.

Tables 7 and 8 show the NO_X emissions obtained from each one of the different phases of cycles: urban, rural and motorway in case the RDE cycle and low, medium, high and extra-high in case the WLTC.

	NO_X_35ºC [g]	**NO_X_20ºC [g]**	**20ºC Vs 35ºC**
Urban	11.795	11.366	-3.63%
Rural	4.577	4.205	-8.12%
Motorway	28.228	25.858	-8.40%
Total	44.60	41.43	-7.11%

Table 7: RDE NO_X emissions by zones.

	NO_X_35ºC [g]	**NO_X_20ºC [g]**	**20ºC Vs 35ºC**
Low	0.829	0.792	-4.46%
Medium	1.182	1.139	-3.67%
High	1.911	1.683	-11.93%
Extra-high	13.857	12.195	-11.99%
Total	17.78	15.8	-11.63%

Table 8: WLTC NO_X emissions by zones.

As tables 7 and 8 present, larger reductions have been registered for higher load zones (Rural and motorway in case RDE; high and extra high in case WLTC). During these zones the highest NO_x emissions are produced as can be observed in fig. 4. Two main reason justify this effect. First a lower mixture temperature, and additionally an EGR rate increase.

To deeply understand the effect of intake temperature and the EGR rate on NO_X emissions, knowing the EGR rate values can be useful. In this way, EGR rate can be easily estimated by means of CO_2 volumetric concentration in the intake manifold [41], as Eq. 5 shows, although this methodology is not very accurate for WLTC and RDE cycles due to the high transient dynamics.

$$EGR_{rate}[\%] = \frac{CO_{2_{INTAKE}}[\%] - CO_{2_{AMBIENT}}[\%]}{CO_{2_{TAILPIPE}}[\%] - CO_{2_{AMBIENT}}[\%]} \; x\, 100 \qquad [7]$$

Nevertheless, EGR rate can also be calculated through engine volumetric efficiency. In order to do that, engine volumetric efficiency has been characterised for several engine speeds by means of specific engine tests without EGR. Later, using a linear regression study, the volumetric efficiency (Vol.eff) can be experimentally characterised (for this specific engine) as a function of the engine speed as Eq.8 shows.

$$Vol.eff[\%] = (0.585 + 0.000193 * n - 0.0000000314 * n^2) \quad [8]$$

Where:

- n = Engine speed [rpm].

Thanks to the volumetric efficiency, the theoretical AMF can be calculated by using the intake temperature and pressure as the Eq.9 shows. The difference between theoretical and measured AMFs represents the EGR mass flow, calculated as shown in Eq.10 which allow to calculate the EGR rate with Eq.11.

$$AMF_{theo.}\left[\frac{g}{s}\right] = Vol.eff[\%] * \left(\frac{P2'[Pa]}{R*(T2'[K])}\right) * D[m^3] * i * z * n[rpm] * \frac{1000}{60} \quad [9]$$

$$EGR_{mass\ flow}[\tfrac{g}{s}] = AMF_{theo.}\left[\frac{g}{s}\right] - AMF_{measured.}\left[\frac{g}{s}\right] \quad [10]$$

$$EGR_{rate}[\%] = \frac{EGR_{mass\ flow}[\frac{g}{s}]}{AMF_{measured.}\left[\frac{g}{s}\right]} * 100 \quad [11]$$

Where:

- R = Universal gas constant [kg/mol*K]
- D = Engine displacement [m^3]

- n = Engine speed [rpm].
- P2’ = water charge air cooler outlet pressure [Pa].
- i = 0.5 (Due to it is a four-stroke engine).
- z = Number of cylinders.

Fig. 5 shows the EGR rates during the RDE and WLTC tests in each one of their zones, calculated through the volumetric efficiency approach, since it is more reliable in transient tests.

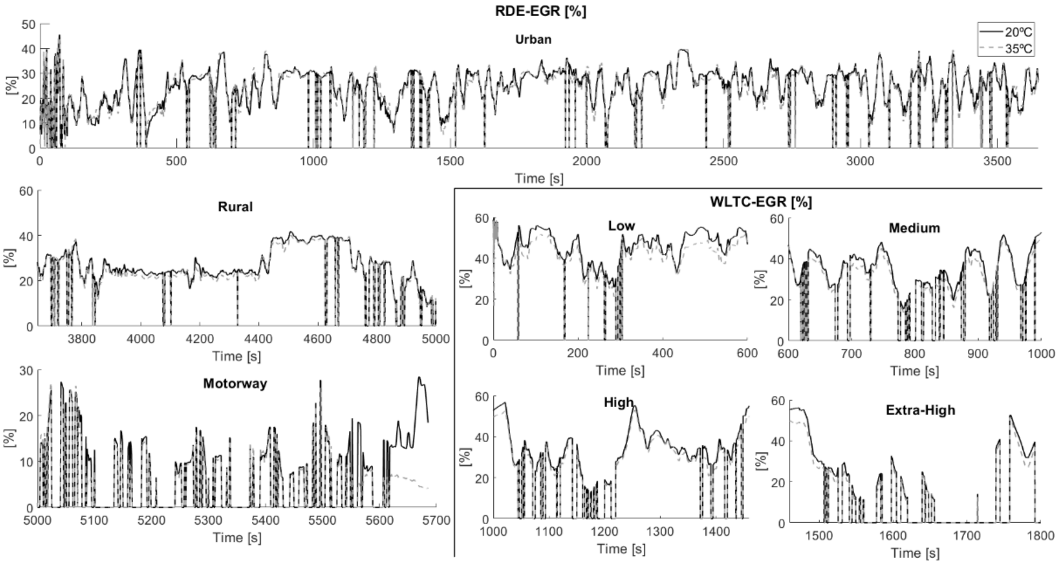

Figure 5: RDE and WLTC EGR rates calculated through volumetric efficiency.

Fig.5 shows that EGR rates are similar for the tests performed with different T2’, nevertheless in the cases of T2’=35ºC slightly lower EGR rates are noticed as it was expected due to the higher intake density in tests at 20ºC. In fact, considering that the

ECU assign the AMF setpoint which only depends on the engine operative conditions and therefore it remains constant for both 35ºC and 20ºC tests, the higher intake air density, the bigger EGR mass flow. EGR valve is used to follow the AMF setpoint. Since the AMF is the same, in case of a higher intake air density, EGR valve position needs to be more open. This reaffirms the drop in NO_X emissions obtained in tests with T2'=20ºC.

To make a deeper analysis, four different fractions of the 4 tests in different phases of the cycles have been analysed. In particular, two situations where the EGR is enabled and two where the EGR valves are completely closed (high load conditions).

As can be observed in fig. 6 during each one of these phases the vehicle speed is high enough and practically does not vary. The fact that the vehicle speed does not change, helps to analyse the engine behaviour since it could be similar to a steady test.

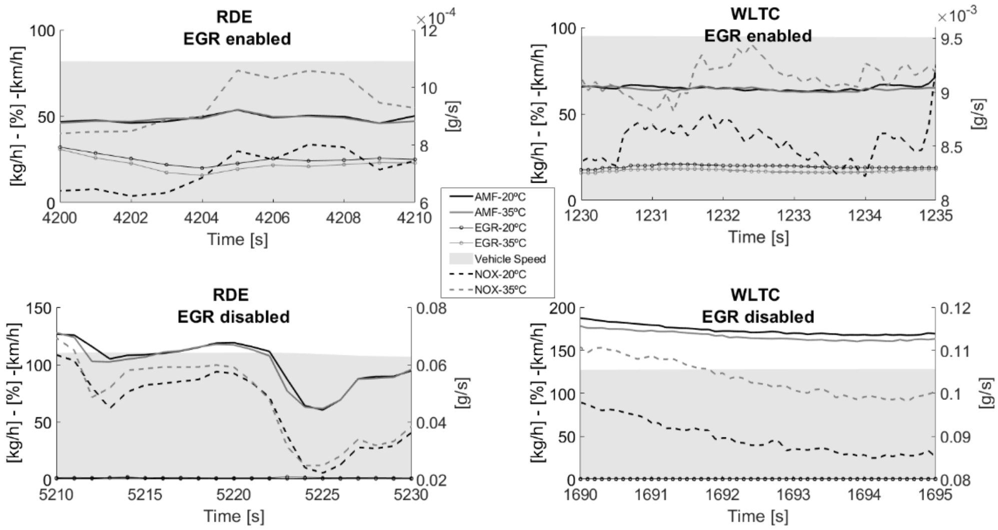

Figure 6: Air mass flow (kg/h), EGR rate (%), Vehicle speed (km/h) and NO_X emissions (g/s) with and without EGR.

Other three variables are represented in the four graphics: Air mass flow (AMF) in kilograms per hour, and EGR rate (%) calculated through volumetric efficiency, are referenced in the left axis and NO_X emissions in grams per second in the right axis.

Figures at the top side show fractions of the test where the EGR valve is open. In the RDE case, EGR rate varies between 40%-20%. In case the WLTC EGR stabilizes around 20%. In both cases AMFs are controlled by look-up tables in the ECU.

Figures at the bottom side present phases where there is not EGR. They can be seen as the two lines that represents EGR rate are overlapped in zero. In these cases, the AMFs are similar, even it is slightly higher in the case of the test at 20ºC. Focusing on NO_x, both tests performed with lower temperature show lower emissions, which would confirm the dependence of emissions on temperature, so lower intake temperatures results in less NO_X emissions.

Fig. 7 shows the lambda values of the same phases shown in Fig. 6. Graphics at the top side show phases when the EGR is activated. Graphics at the bottom side show phases when the EGR is disactivated due to high dynamic solicitations.

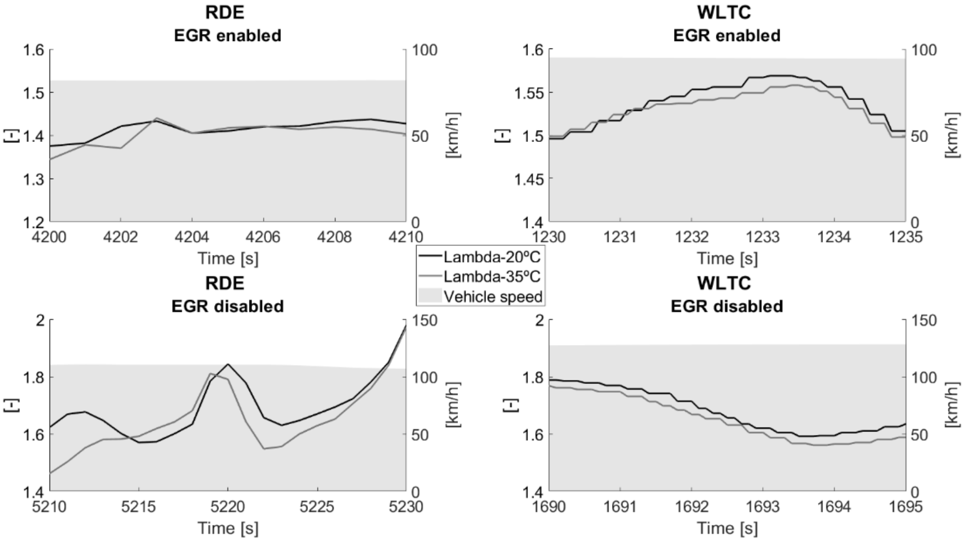

Figure 7: Lambda values measured.

Higher values of lambda can be observed in the case where the intake temperature is lower, which represents lean conditions. The increase of lambda when EGR is activated is produced by two reasons. The first reason is the increase of oxygen in the combustion chamber. In this case, two situations must be analysed. Effectively, at part load, the AMF is regulated by the ECU, but as the intake density grows up, the EGR flow must increase (the engine aspirates more mixture). In this case, the lambda increase is due to the supply of oxygen from the EGR flow to the combustion chamber. Second situations, appears at high loads (EGR disabled), the ECU does not control the air but the intake pressure, which is why the lower temperature (higher density) causes the air flow (oxygen) to increase.

The second reason is the fuel consumption reduction, produced by the small increase of the engine efficiency. Figure 8 and tables 9 and 10 show a small CO_2 reduction which justifies the fuel consumption reduction. This effect appears as a consequence of the higher oxygen quantity at the combustion chamber [42].

Fig. 8 shows the tailpipe CO_2 measurements. In the left axis, instantaneous values with solid lines are represented. In the right axis, dashed lines represent the accumulated values.

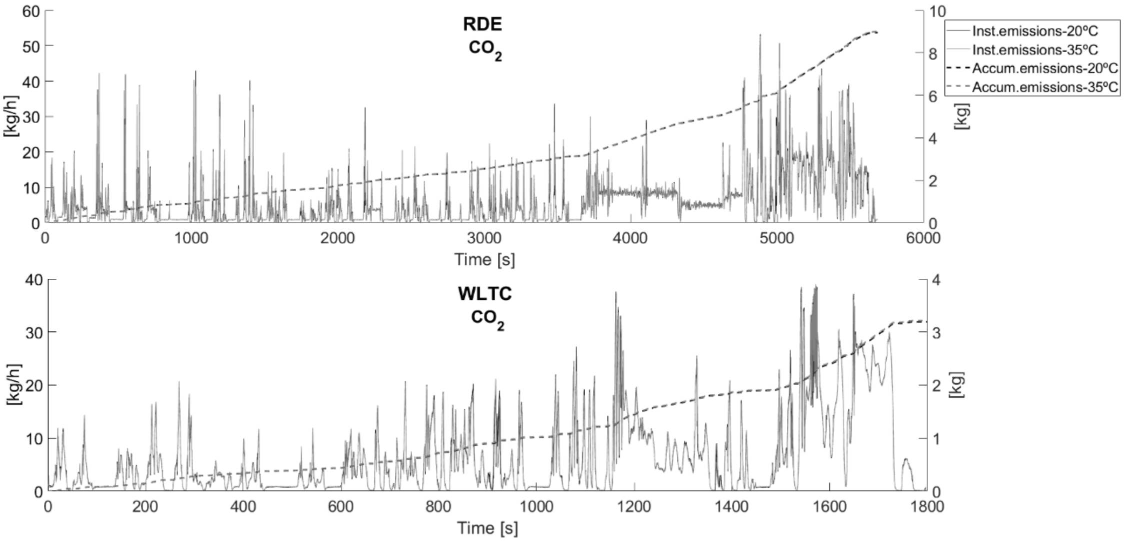

Figure 8: Instantaneous and accumulated CO_2 emissions.

Lines in fig. 8 do not show divergences between the tests, and all the lines are practically overlapped. However, the final values shown in tables 9 and 10 present some differences.

	CO_2_35ºC [kg]	**CO_2_20ºC [kg]**	**20ºC Vs 35ºC**
Urban	3.135	3.138	0.11%
Rural	2.935	2.931	-0.11%
Motorway	2.932	2.886	-1.55%
Total	9.002	8.957	-0.50%

Table 9: RDE CO_2 emissions by zones.

	CO_2_35ºC [kg]	**CO_2_20ºC [kg]**	**20ºC Vs 35ºC**
Low	0.50	0.49	0.36%

Medium	0.58	0.57	-0.37%
High	0.87	0.85	-1.31%
Extra-high	1.28	1.26	-1.56%
Total	3.22	3.191	-0.98%

Table 10: WLTC CO_2 emissions by zones.

Both RDE and WLTC tests point out a better performance in terms of CO_2 emissions in case the test at 20ºC. Reductions of 0.50% and 0.98% respectively have been obtained. It confirms the premise of an improvement in engine performance by lowering the engine inlet temperature, due to a higher air fuel ratio (AFR), which involves the combustion to be developed with more O_2 excess. This aspect causes a more complete combustion, an earlier start of the combustion processes since the mixing time is reduced [42]. The O_2 concentration at the exhaust (tailpipe) can be checked to corroborate this condition. Fig. 9 shows the oxygen concentration measured during a specific part of RDE urban zone, where the vehicle is stopped at the beginning, performs an acceleration, maintains a certain vehicle speed and finally brakes and comes to stop. In the left axis, the O_2 concentration values with solid lines are represented. The vehicle speed is represented in the right axis.

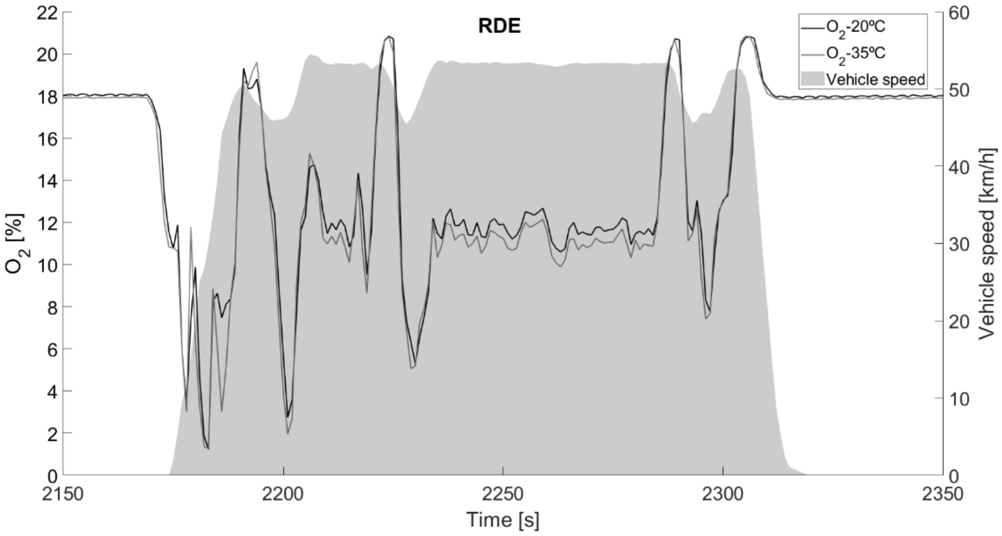

Figure 9: O_2 concentrations and vehicle speed during a specific part of RDE urban zone.

As can be observed in fig. 9, higher O_2 concentrations are measured when the test is carried out with 20ºC intake temperature setpoint. The O_2 increments, as in the case of lambda, can be analysed in two different situations. First, when the EGR is controlled, for a given engine conditions, the AMF is set constant independently of T2’. In this case, an EGR flow increase is produced as a result of a higher intake density. This new EGR quantity contains a O_2 concentration determined with the AFR. Since the AMF is constant but the fuel consumption has been reduced, the AFR increases which forces a gain of O_2 concentration in the exhaust gases.

The other case appears when EGR saturation conditions are reached (EGR valve fully opened and back pressure valve fully closed) or the EGR is disabled. In these conditions the higher air density involves an AMF increase with the subsequent O_2 gain.

On one hand it indicates a more efficient combustion, which explains the improvements in CO_2. On the other hand, although a priori, a major quantity of oxygen would produce a greater NO_X emission, it was proved previously that they were reduced, mainly due to a high EGR rate and consequently, lower combustion temperature.

Concerning the CO and THC emissions, fig. 10 shows the accumulative emissions. The vehicle speed profile is also represented in grey shadows, having the data at the right axis.

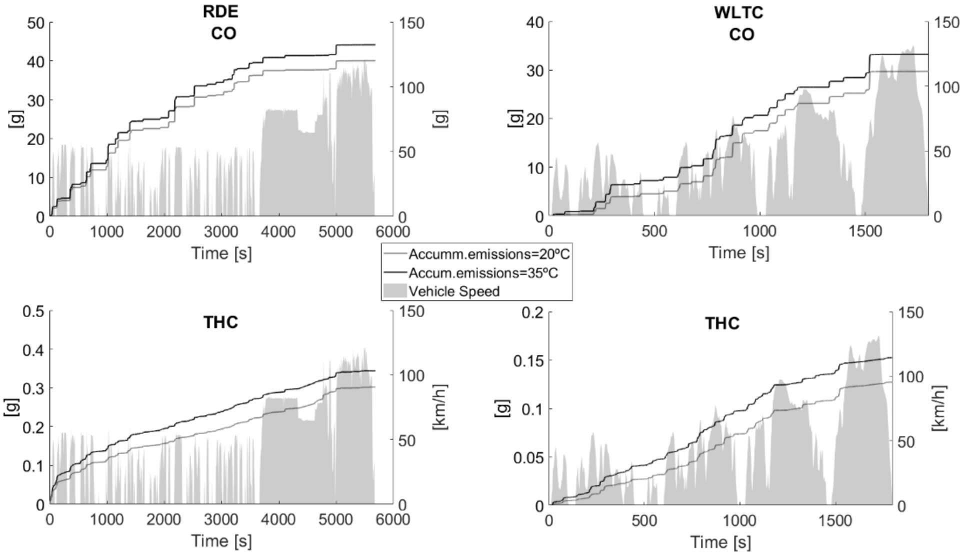

Figure 10: Vehicle speed profile and accumulated THC and CO emissions.

In fig. 10 it can be observed that a large part of THC emissions is produced during the warming-up of the engine and aftertreatment systems. After that, THC emissions present an almost constant value since no great slope changes in the accumulated emissions are observed. However, CO emissions show constant fluctuations. The large steps are produced during strong accelerations, as observed in the vehicle speed profile. Tables 11 and 12 show CO and THC emissions by zone of the cycle and total values.

	CO_35ºC [g]	**CO_20ºC [g]**	**20ºC Vs 35ºC**	**THC_35ºC [g]**	**THC_20ºC [g]**	**20ºC Vs 35ºC**
Urban	36.290	39.574	-8.30%	0.273	0.223	-18.25%
Rural	1.666	2.054	-18.88%	0.056	0.068	21.07%
Motorway	2.087	2.506	-16.72%	0.015	0.012	-24.33%
Total	40.043	44.134	-9.27%	0.344	0.302	-12.15%

Table 11: RDE CO and THC emissions by zones.

	CO_35ºC [g]	**CO_20ºC [g]**	**20ºC Vs 35ºC**	**THC_35ºC [g]**	**THC_20ºC [g]**	**20ºC Vs 35ºC**
Low	5.07	7.94	-36.18%	0.032	0.048	-33.48%
Medium	12.44	12.75	-2.44%	0.042	0.050	-15.91%
High	7.73	7.76	-0.41%	0.034	0.038	-8.96%
Extra-high	4.49	4.78	-6.11%	0.019	0.017	12.80%
Total	29.72	33.22	-10.54%	0.127	0.152	-16.54%

Table 12: WLTC CO and THC emissions by zones.

All the results denote a decrease of CO and THC when running with colder intake temperature. Lower CO emissions obtained at lower temperature are due to the AFR increase, involving more oxygen proportion that helps to oxide the CO. Although THC emissions are usually higher at low temperature, in case of T2'=20ºC, the higher AFR compensates this effect and the THC emissions are lower.

5. CONCLUSIONS

RDE and WLTC tests have been performed on a light duty euro 6 diesel engine, installed in a climatic engine test bench. The tests have been carried out by setting different intake air temperature: 20ºC and 35ºC. Significant drops in NO_X, 7.1% in RDE cycle and 11.63% in WLTC have been measured in case the tests were performed at 20ºC. According to [43] it is possible to confirm these improvements with a confidence interval of the 95%, since the feasibility of the test bench were proved and the results presented an uncertainty of 3.13% and 3.9%, respectively for the RDE and WLTC cycles.

A not negligible increase of EGR mass flow has been noted when the tests were performed at low temperature (20ºC) due to the higher intake density. As fresh air mass flow has been controlled by the Electronic Control Unit (by regulating the EGR valve), higher intake density produces more EGR mass flow (additional EGR). As a consequence, a reduction of NOx emissions has been obtained from tests performed at 20ºC. This reduction is also produced due to the lower intake temperature.

Small differences on CO_2 emissions have been registered when comparing tests at different intake temperature. A reduction of 0.5% and 0.98% for RDE and WLTC have been respectively obtained for tests at 20ºC.

During both the engine and the aftertreatment devices warming- up, a great amount of THC and CO are registered in any case. These emissions have always been lowered in case of tests with T2'=20ºC, as a result of the air density increase, which produces an O_2 gain in the combustion chamber.

Author contribution

Luján, J.M.: Term, Conceptualization, Writing Original Draft, Supervision.

Climent,H.: Methodology, Writing Original Draft.

Ruiz, S: Technical support; Test Bench Experimental tests follow up.

Redondo, F.: State of the art Review, Investigation, Experimental Data Validation, Writing Original Draft, Editing.

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