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Title:

Engine test bench feasibility for the study and research of real driving cycles. Pollutant emissions uncertainty characterization.

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ABSTRACT

The future of Internal Combustion Engines in the automotive sector seems uncertain, to some extent due to the recent changes in type approval regulations. Current regulations have considerably reduced the engine pollutant emissions limits, as well as introduced more demanding testing conditions. The introduction of real driving cycles presented a challenging issue for car manufacturers when homologating their vehicles, since the traditional and undemanding NEDC (New European Driving Cycle) certification cycle has been replaced by sever cycles as WLTC (World Light Duty Test Cycle) and RDE (Real Driving Emissions).

This document presents a methodology for implementing a RDE cycle in an engine test bench. Even knowing that the essence of RDE regulation is to assess actual driving conditions, reproducing RDE cycles in a test bench is of great interest, since the controlled and reproducible conditions that can be achieved in a laboratory lead to valuable information to understand engine behaviour in real driving conditions, and therefore contribute to engine development. This document applies the most recent European Community regulation and sets the essential steps to carry out a RDE cycle in an engine test bench.

Once the WLTC and RDE cycles were implemented, this study analyses the uncertainty and repeatability of the values obtained in successive repetitions of the test, carried out under the same conditions. Uncertainty values are obtained on the most representative parameters of engine operation, as well as pollutant emissions. One of the most relevant contributions of this study is to obtain the uncertainties of type approval pollutant emissions. As an example, the uncertainty obtained by applying the methodology described in this article on nitrogen oxide emissions (NOx), considered one of the most relevant pollutant emissions of diesel engines, has been extremely reduced, obtaining values of 3,13% and 3,9%, respectively for the RDE and WLTC cycles.

Abbreviations

- CF = Conformity factor.
- CO = Carbon Monoxide.
- CO_2 = Carbon Dioxide.
- DOC = Diesel oxidation catalyst.
- DPF = Diesel particulate filter.
- GPS = Global positioning system.
- HCNM = Non-methane Hydrocarbons.

- MAW = Mobil average windows.
- NEDC = New European Driving Cycle.
- NO_X = Nitrogen oxides.
- NTE = Not to exceed.
- PB = Power binning.
- PEMS = Portable emission measurement system.
- PM = Particulate Matter.
- PN = Particulate Number.
- RDE=Real Driving Emissions.
- RF = Result evaluation factor.
- RPA = Relative position acceleration.
- SCR = Selective catalytic reduction.
- THC = Total Hydrocarbons.
- WLTC= Worldwide Light-duty Test Cycle.

1. INTRODUCTION

The light duty vehicle fleet has been considerably increased during the last decades. Currently, there are more than 1.2 billion vehicles in the world according to OICA (International Organization of Motor Vehicle Manufacturers) [1]. With the world population increasing to more than 11 billion in 2100, according to the ONU [2], and the development of countries such as China and India (Global Economic Prospects, World Bank Group) [3], the number of vehicles will continue to rising.

Most of these vehicles are equipped with internal combustion engines, that use fossils fuels as its main energy source. In addition, despite the number of electric vehicles has increased in recent years, achieving a share of 5,1 million in the world according to the International Energy Agency (IEA) [4], they only represent a 0,4% of the total. Furthermore, the internal combustion engines will have a big importance in the ecological transition in the next decades improving their efficiency and incorporating hybrid solutions [5].

In the second half of the twentieth century, the negative impacts of the engines exhaust gases were pointed out by the research community. These gases affect humans and the environment. The adverse effects are mainly appreciated above all in big cities with traffic jam problems. The poor air quality is a big issue for human health. It is estimated that approximately 3% of cardiopulmonary and 5% of lung cancer deaths are attributable to PM (Particulate matter) globally according to World Health Organization [6]. The first regulation restricting the emissions of pollutant gases was stablished in California in the 60s [7]. Years later, the first pollutant emissions regulation for vehicles appeared in Europe, known as EURO 1 regulation [8], its first version was introduced in 1992, by delimiting the emissions of nitrogen oxides, unburned hydrocarbons, carbon monoxide, and particulate matter. To certify that the limits of each one of these substances had been accomplished, the NEDC type approval cycle was stablished in 2000 [9]. This cycle has to be performed in a rolling test cell facility. Over the years, the limits of each one of these substances has been reduced [10], with the final purpose that car manufacturers design engines committed with the environment and human health. The fulfilment of these limits was verified with the NEDC. However, the NEDC became questioned years later, since it is a undemanding cycle for current engines and vehicles, whose power and performance have been increased over the years. Consequently, the type approval emissions have been reduced in an order of magnitude (6,25 times in the case of NO_X) during the last decade, whereas real driving emissions have been decreased only by 40% on average between Euro3 and Euro6 [11]. In other words, real driving emissions are substantially higher than emissions under type approval conditions, with variable factors from 4 to 10 times depending on the source [12].

This situation was known by the European Union a long time ago, and there are reports, such as the report drawn up by the JRC (Joint Research Centre-Institute for Energy), an Institute depending on the European Commission [13]. Other reports elaborated by independent organizations such as the ICCT, [14] and [15] arrive to similar conclusions.

These issues were revealed after the ``diesel gate´´ scandal [16], finding out that most of the vehicles, not only Volkswagen cars, widely surpassed the emission limits imposed by regulation when being driven in the street. As a consequence, NOX and particles concentrations are higher than recommended, especially in big cities subject to dense traffic [17].

The European Commission drafted a report about the automobile emissions measurement, finding out big differences between emissions in the NEDC and road emissions, blaming on manufacturers for this fact [18].

To cope with this situation, the European Commission recently stablished a relevant modification concerning the evaluation of pollutant emissions limits. This modification consists in the implantation of two new cycles, WLTC and RDE described for first time in the regulation in 2016 [19]. The WLTC is performed in a chassis dynamometer, as well as NEDC, but with different characteristics and requirements. WLTC conditions are more demanding than NEDC, not only due to the higher duration, but also to the higher the power needed to follow the speed profile as a consequence of more aggressive accelerations and higher percentage of the cycle with high speeds. These requirements extend the engine operating map, giving emission information in a wider operation zone including high load conditions.

In the other hand, the European Regulation [19] introduced the RDE as a method to assess vehicle emissions during real driving conditions. In order to register pollutant emissions, a PEMS (Portable Emissions Measure System) must be used.

But despite the RDE regulation stablishes that to consider a cycle valid it must fulfill many conditions, different cycle alternatives are infinite. Traffic, climatological conditions, and different driver behaviours can produce many different cycles. Of course, those cycles may lead to different pollutant emissions and fuel consumption, so even following the same route, they may produce different results in terms of homologation purposes.

Provided that RDE stablishes some limits to the driving conditions to consider the cycle valid for pollutant emissions assessment, it may happen that that a RDE test is aborted due to deviations from the admitted range in the operating conditions or even that, after finishing it, engineers realize that the cycle is not valid.

Nowadays, it is easy to find research works that deal with the optimization of different control systems and strategies that allow minimizing the fuel consumption and emissions of the engines in transient evolutions. In general, these strategies are applied to the specific defined cycles as the WLTC, reaching very satisfactory results that, in many cases, are validated with tests in experimental laboratory facilities (rolling test benches or engine test cells) [20, 21]. There are also many publications in which these results are obtained by simulation, which entails a substantial cost reduction compared to physical vehicle testing [22].

However, it is difficult to carry out these validations for real driving situations, where it is necessary to reproduce certain engine operating conditions on the road.

Another problem is the lack of repeatability found on road cycles. If the driver changes, big dynamical differences can be found [23]. Even if on road cycles tries to be repeated with the same driver and conditions, issues can appear which spoil the test (DPF regeneration, traffic jams…). Testing on road cycles even following the same route, has great NOx emissions dispersion [24], with final emissions differences higher than 24% [25]. Furthermore, PEMS has smaller precision than stationary laboratory equipment [26].

In this sense, reproducing RDE cycles under controlled conditions in the laboratory is a challenge that has been considered by the different research groups [27].

An option to mitigate the repeatability problem is to transfer the dynamic conditions obtained in an RDE Cycle done on road with a PEMS to an engine test bench, so although finally it is necessary to perform the RDE on road, reproducing its conditions to a test bench, this could help to many development works.

Implementing these real driving conditions in an engine test bench environment is possible thanks to the software capacity to simulate driving conditions. So, reproducing the RDE test in an engine test bench allows to, after comparing the obtained results with those in the real route, take profit of the test bench higher instrumentation and control capabilities to obtain accurate results that asses the performance of the engine and allow to carry out specific studies aimed to improve the engine performance in this particular route.

After that, comparatives, or many parametric studies in the same RDE cycle can be done, without being affected by traffic and climatology conditions or driving behaviour.

Using this methodology, studies aimed to reduce pollutants emissions and fuel consumption can be fully performed with accuracy guarantees. For instance, implementing new driving behaviour strategies, engine control, trying different engine components, bodyworks with better drag coefficient or climatic conditions studies, tasks already done in WLTC and NEDC cycles [28].

The aim of this paper is to study the viability and assess the uncertainty of performing RDE and WLTC cycles in an internal combustion engine test bench.

Test benches have been traditionally used to test engines under several stationary, or transient conditions, but a work on the determination of the variability of measurements before full RDE cycles has not been found in literature. These cycles, due to their long duration, as well as their range of use of the engine, and the numerous and rapid transient evolutions to which the engine is subjected, force the engines to behave in a non-repetitive way (mainly due to non-repetitive control actions of systems such as turbocharger, EGR or injection systems). So, it has been considered quantifying and limiting these discrepancies, in order to be able to rigorously determine the improvements that can be obtained from the engines due to the changes in their components or control strategies.

To make this possible, the repeatability and reproducibility of different tests cycles will be studied trying to keep the same conditions, so it is necessary to consider the accuracy and uncertainty of all the measurement systems that can be used.

The study on the WLTC will help to assess the uncertainty in the main variables measured in the engine test bench such as pressures, temperatures, mass flows, pollutant emissions etc in a driving cycle.

After that, the analysis of RDE cycles entails a step beyond, since it assumes that the test is carried out in a real route. All the improvements that could have been found in the research work carried out in the test cell, will be finally confirmed on the route.

2. RDE CYCLE REQUIREMENTS

The RDE appeared as a type approval test in the (2016/427) regulation [19] in March 2016. At the beginning, two different validation methodologies coexisted to evaluate pollutant emissions, MAW (Mobil average windows) and PB (Power binning) [29]. In 2017, with 1151/2017 regulation [30] and later on in 2018 with 1832/2018 regulation [31], the European Commission made some changes in the methodology since the adoption of two different methods (MAW and PB) lead to incoherent results and often invalid tests, [32]. In particular, the application of the two methods show noticeable differences in the emission rates that can range from 10% to 45% depending on the considered pollutant [33]. After that, PB was removed, and MAW was modified, due to incoherent results [34]. MAW is no more use to emissions calculation, but it is needed to certify the validity of the cycle. In addition, the emissions during the cold start period that before were not considered, shall be included in the evaluation of the results. Additionally, a new concept known as RF (Result evaluation factor) was introduced to calculate the final emissions.

Currently, the regulation stablishes three steps with different types of conditions that must be completed.

STEP A:

- Climatological conditions.
- Altitude.
- Dynamic route requirements.

STEP B:

- RPA (Relative position acceleration).
- va[95].
- Cumulative altitude gain.

STEP C:

- MAW.

Step A, assess that the driving cycle is carried out respecting limits on ambient, altitude and route conditions. For every single criteria, the regulation stablishes a minimum and maximum threshold.

Step B introduces the calculation of two parameters describing the driving cycle dynamics. The first one, the RPA is an average acceleration calculated for each zone. This value must be above a calculated threshold, based on average speed in each cycle zone (urban, rural, motorway).

The second parameter, va(95), is the 95th percentile of the product of vehicle speed and positive acceleration (only when the instantaneous acceleration is higher than 0,1 m/s^2) for urban, rural and motorway driving. It must be less than another threshold, that also depends on the average speed in each zone.

Furthermore, in this step the cumulative altitude gain is calculated, and it should be lower than 1200m/100km.

The last step, step C, consists of the calculations of MAW. First, to carry out this step, a WLTC must be performed in order to obtain a CO_2 reference mass value consisting in half of the CO_2 mass emitted by the vehicle during the test. Finally, averaged emissions and engine speed at low, medium and extra-high zones are calculated from WLTC data. Once the average values were obtained, a reference CO_2 curve can be calculated. An example of this curve is shown in section 5.

The CO_2 mass reference is used to calculate the average windows that will be used for RDE cycle analysis. Using a sampling frequency of 1Hz, CO_2 emissions will be cumulated until they reach the CO_2 reference. During this period, the average speed in km/h and the average specific emissions of CO_2 in g/km calculated and it will be obtained the first window. Next window will start a second later than the first one and the same calculation will be done until the cycle is over. And finally, the test is valid when it comprises at least 50% of the urban, rural and motorway windows that are within the tolerances defined for the CO_2 characteristic curve.

If the three steps have been met successfully, the emissions calculation can be done as described in appendices 4 and 6 of the regulation [30]. In order to do that, the RF obtained from the CO_2 emissions ratio of RDE and WLTC needs to be used. This RF factor allows reducing the RDE emissions if the performed RDE cycle has higher CO_2 specific emissions than those obtained in the WLTC. It is applied throughout the entire route and in the rural zone.

Once it is applied, in order to obtain the type approval conformity report, total and rural specific emissions have to be under the limits of Euro 6 regulation. Nevertheless, since developing a vehicle to meet the regulation limits in wide range of driving conditions as proposed by RDE has a massive impact in all the aspects of the powertrain development, Conformity Factors (FC) were introduced, with the aim of relaxing, at least temporarily emissions limits. In this way Not to Exceed limits (NTE) for RDE are according to equation (1). Table 1 shows Euro 6 limits of NO_X (Nitrogen Oxides), THC (Total Hydrocarbons), HCNM (Non-methane Hydrocarbons), CO (Carbon Monoxide), PN (Particulate Number) and PM (Particulate Matter).

$$NTE_{pollutant}=CF_{pollutant} * \text{Euro } 6_{pollutant} \qquad (1)$$

EURO 6													
NO_X		**THC + NO_X**		**THC**		**HCNM**		**CO**		**PN**		**PM**	
mg/km		*mg/km*		*mg/km*		*mg/km*		*mg/km*		*#/km*		*mg/km*	
PI	CI	PI	CI	PI	CI	PI	CI	PI	CI	PI	CI	PI	CI
60	80	-	170	100	-	68	-	1000	500	6E11	6E11	4,5	4,5

Table 1: Euro 6 pollutant emission limits. PI=Positive ignition, CI=Compression ignition.

Initially, in the Euro 6d-temporary it was stipulated a conformity factor of 2,1 for NO_X emissions, which was cut down to 1,43 in the final Euro6d. The CF for PN is 1,5. These reductions will complicate even more the regulation fulfillment.

3. MATERIALS AND METHODS

3.1 Simulated vehicle

The vehicle simulated in the engine test bench was the same used on road (a passenger car). In order to perform the simulation, many different car and gear box characteristics need to be introduced in the simulation software. Data of these parameters are shown in table 2.

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
	1ª	*Vehicle speed (km/h at 1000 rpm)*	8,69
	2ª		16,42
	3ª		25,42
	4ª		37,77
	5ª		48,79
	6ª		57,32

Table 2: Vehicle Characteristics.

Furthermore, the driver behaviour, the selected gear box, and the clutch operation are also needed to be programmed.

The engine characteristics are shown in the table 3:

Engine Characteristics		
Fuel		Diesel
Aspiration		Supercharged
Engine capacity	cm^3	1598
Max. Power	*kW/rpm*	96/4000
Max. Torque	*Nm/rpm*	320/1750-2500
Aftertreatment system		DPF/DOC

Table 3: Engine characteristics.

This engine was designed to fulfill with Euro 5 regulation, where the pollutant limits were verified with a NEDC. Both high pressure and Low pressure EGR (Exhaust gas recirculation) systems, DPF (Diesel Particulate Filter) and DOC (Diesel Oxidation Catalyst) systems permits not to exceed the limits of the Euro 5 regulation. SCR (Selective catalytic reduction) system was not implemented in this engine.

3.2 Engine test cell

The test cell is equipped with different measurement and safety elements, highlighting the following:

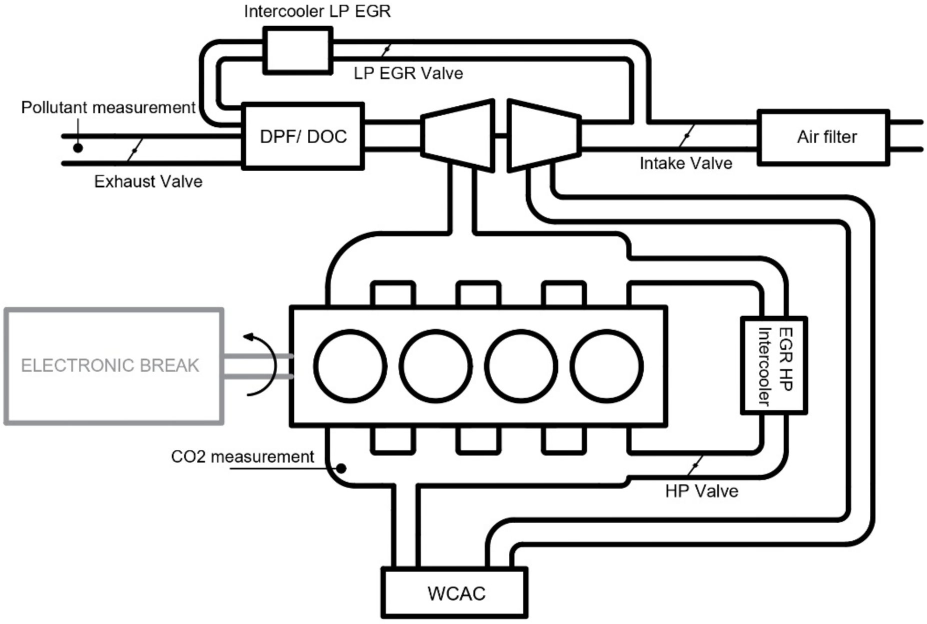

Figure 1: Test cell layout.

- **Electromagnetic brake:** It is essential for the simulation of real driving, due to its capability of adapting the resistant torque to the driving cycle characteristics. The resistance includes the aerodynamic, friction, and inertia forces.
- **Exhaust gas analyser:** Data of O_2, HC, NO_X, CO_2 y CO volumetric concentrations were registered at the tail pipe of the engine. CO_2 concentration in the inlet manifold was also registered to calculate the EGR rate. Uncertainty of measurement is plotted in the figure 2.

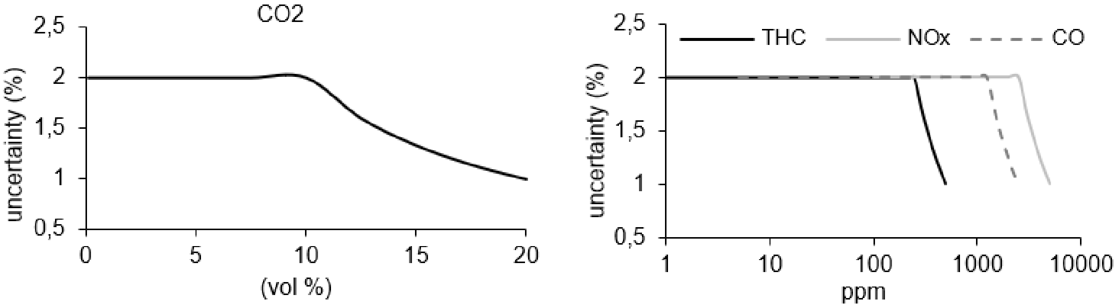

Figure 2: Pollutant emissions uncertainty.

4. RDE and WLTC OPERATIVE CONDITIONS

The WLTC is fully defined by regulation, so the instantaneous vehicle speed and the engaged gear are used by the road load simulation module of the test bench to impose the corresponding resistant torque to the engine.

In order to set the RDE cycle conditions in a test bench, a specific cycle was used as baseline. This cycle on road was performed in Valencia, Spain. The required data to implement a RDE cycle in the cell was collected by GPS and PEMS installed in the vehicle. The figure 3 shows vehicle speed, and power versus time for the cycle performed on road, and the cycle performed in test bench.

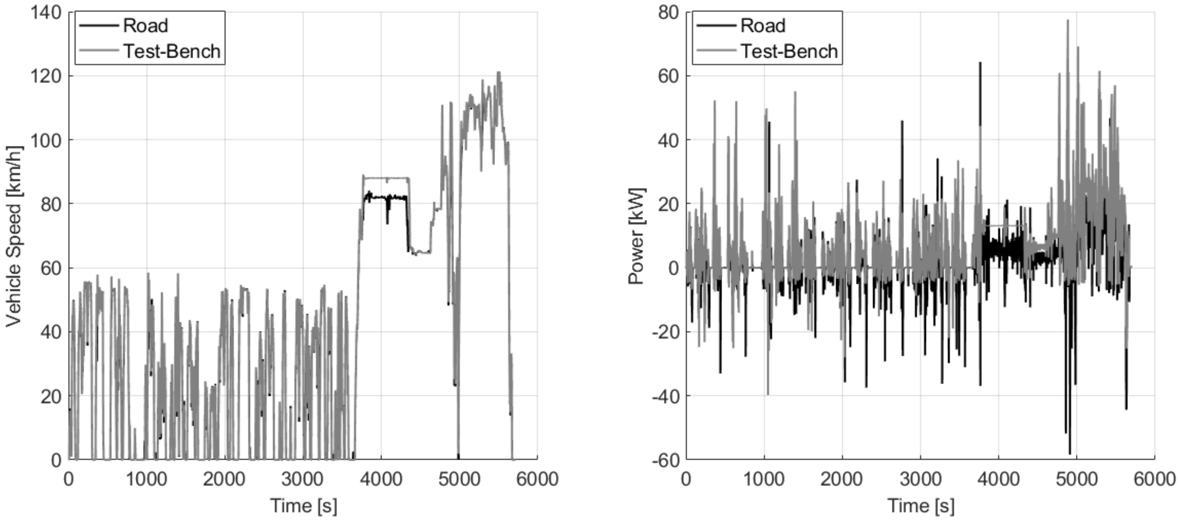

Figure 3: RDE on road, versus RDE in the test bench

As it can be observed in the left side of the figure 3, the vehicle speed changes in a specific section. This modification was necessary to fulfil latest regulations. As a consequence, the results obtained are not the same. So, it is not possible to compare the results obtained in both cycles. Furthermore, the engines used are not the same, and therefore have different ECU, operating maps, aftertreatments…etc

This RDE cycle is divided into three zones, urban, rural, and motorway. Table 4 shows the cycle characteristics.

		Urban	**Rural**	**Motorway**
Average speed	***km/h***	21,73	79,72	99,99
Time	***s***	3906,00	1142,00	733,00
Distance	***km***	23,57	25,29	20,36

Table 4: RDE characteristics

Once the cycles have been performed, figure 4 represents values obtained from the test bench experiment. The figure on the top shows the vehicle speed, while middle and the bottom plots represent the engine torque and speed evolutions.

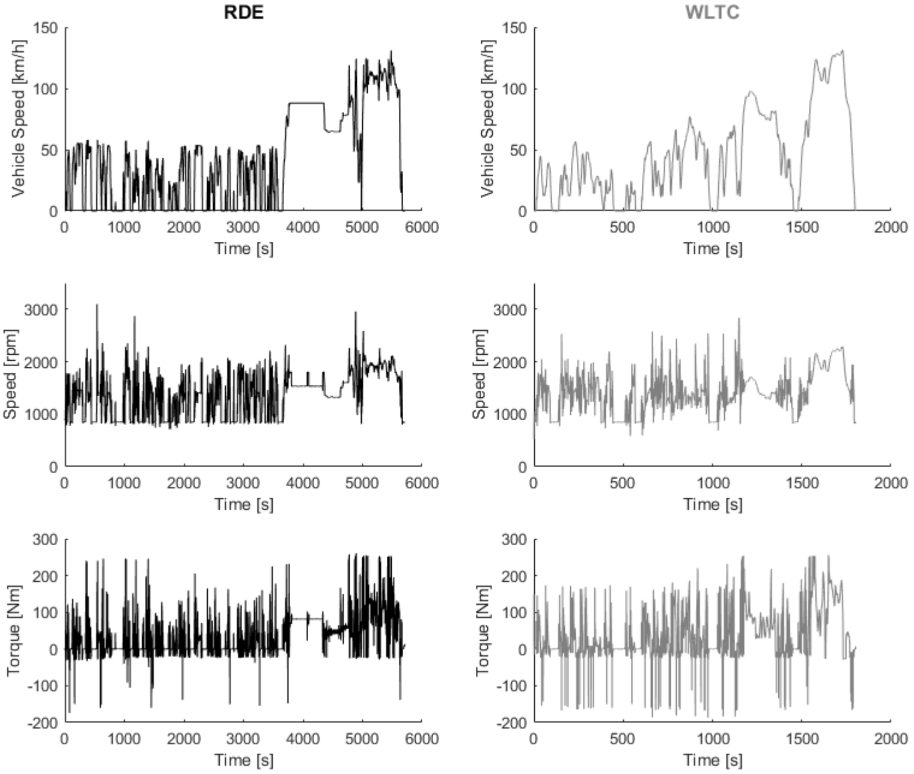

Figure 4: RDE and WLTC engine speed and torque results.

Figure 5 shows the instantaneous acceleration versus the vehicle speed for both cycles.

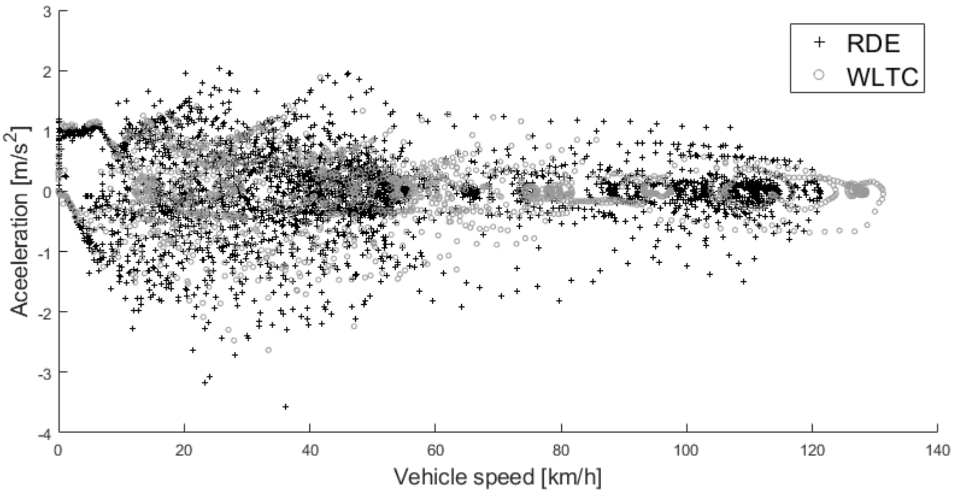

Figure 5: Acceleration distribution.

As can be observed, both cycles have a similar distribution of engine torque and speed.

5. RDE VALIDATION

Before dealing with the result analysis, it has to be verified that the RDE cycle is valid. So, the three steps previously commented in section 2 were checked. Column on the right in table 5 indicates the obtained values of the specific RDE that has been analysed. It can be observed that all the parameters are within specifications.

Step A:

		Min value	Max value	Obtained value
➢ ***Route requirements***				
Duration	***min***	90	120	95
Altitude	***m a.s.l.***	0	700	6
Temperature	***ºC***	0	30	20
Altitude difference (Start-End)	***m a.s.l.***		100	0
➢ ***Urban zone***				
Distance	***Km***	16	-	23,85
Distance proportion	***%***	29	44	34,30
Stop time (idle)	***%***	6	30	29
Longer stop	***%***	-	80	10,21
Average speed	***km/h***	15	30	21,76
➢ ***Rural zone***				
Distance	***Km***	16	-	25,37
Distance proportion	***%***	23	43	36,50
➢ ***Highway zone***				
Distance	***Km***	16	-	20,30
Distance proportion	***%***	23	43	29,20
Time speed >100 km/h	***min***	5	-	8,96

Table 5: RDE constraints and obtained values.

Step B:

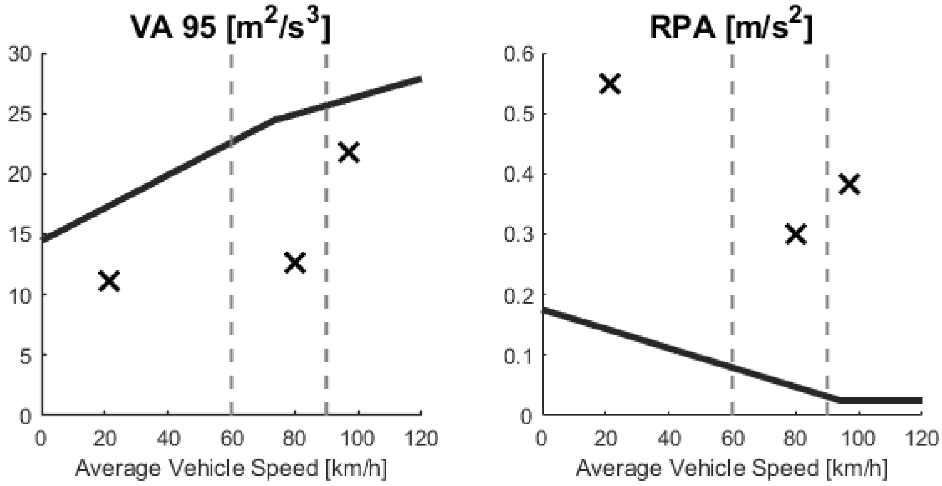

Figure 6: va[95] and RPA.

Crossed marks in figure 6 represent the specific values of va[95] and RPA. It can also be confirmed that, as the values are below and under their thresholds respectively, the performed cycle is valid. The cumulative altitude gain is 0, since road gradient simulation has not been incorporated to the test.

Step C:

Step C, which corresponds to the MAWs, is completely validated since at least 50% of the windows are included inside the tolerances as figure 7 shows.

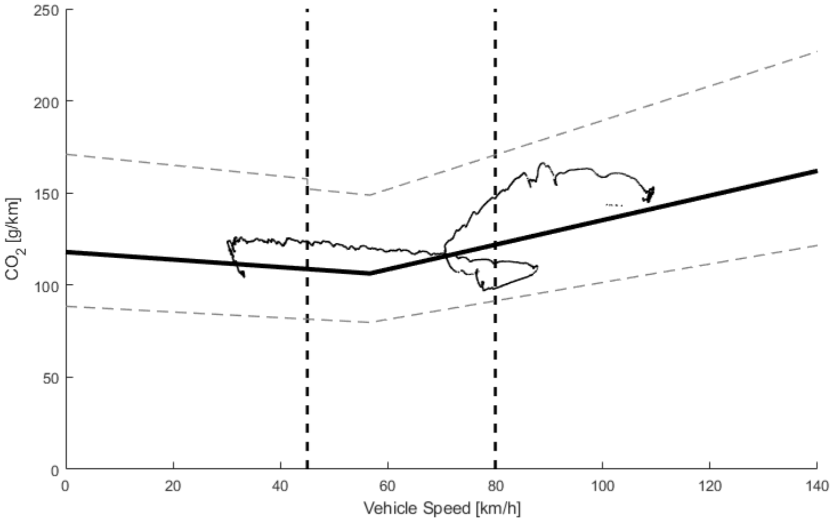

Figure 7: CO$_2$ curve, tolerances and MAWs obtained.

6. WLTC AND RDE TEST DATA

Several repetitions of RDE and WLTC have been carried out for both cycles in the test cell. Similar engine power is observed in both WLTC and RDE tests. Although maximum values of power for RDE cycles are considerably higher, no big differences were observed when comparing WLTC and RDE figures at the different cycle phases. The table 6 summarizes the results.

		WLTC	RDE
Average power	***kW***	7,07	6,71
Max Power	***kW***	55,21	76,72
Average load	***%***	7,36	6,99
High load	***%***	57,51	79,92

Table 6: WLTC and RDE comparison.

In order to obtain the uncertainty of the data, once the WLTC and RDE cycles was implemented on the test cell, the selected RDE cycle has been repeated six times. Four repetitions have been performed in the case of WLTC.

Apart from torque, speed, mass flows, temperature and pressure measurements, the tail pipe type approval pollutant emissions have also been registered, excepting particulate number and particulate mass Particulate Number and Particulate Matter which have not been measured. As an indication of fuel consumption, CO$_2$ emissions are also considered.

Figure 8 shows instantaneous emissions measured of NO$_X$ and CO$_2$.

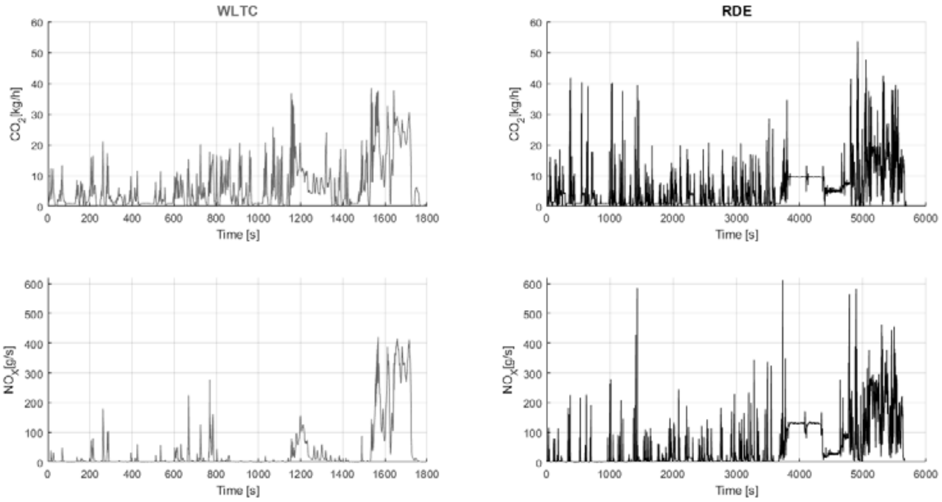

Figure 8: Instantaneous NO_X and CO_2 emissions.

Higher emissions peaks in the RDE cycle for both substances confirming that it is a more aggressive cycle.

Figure 9 presents pollutant emissions for each repetition. These are divided in different zones. Urban, rural and motorway zones in case the RDE, while low, medium, high, and extra high zones have been considered in case WLTC.

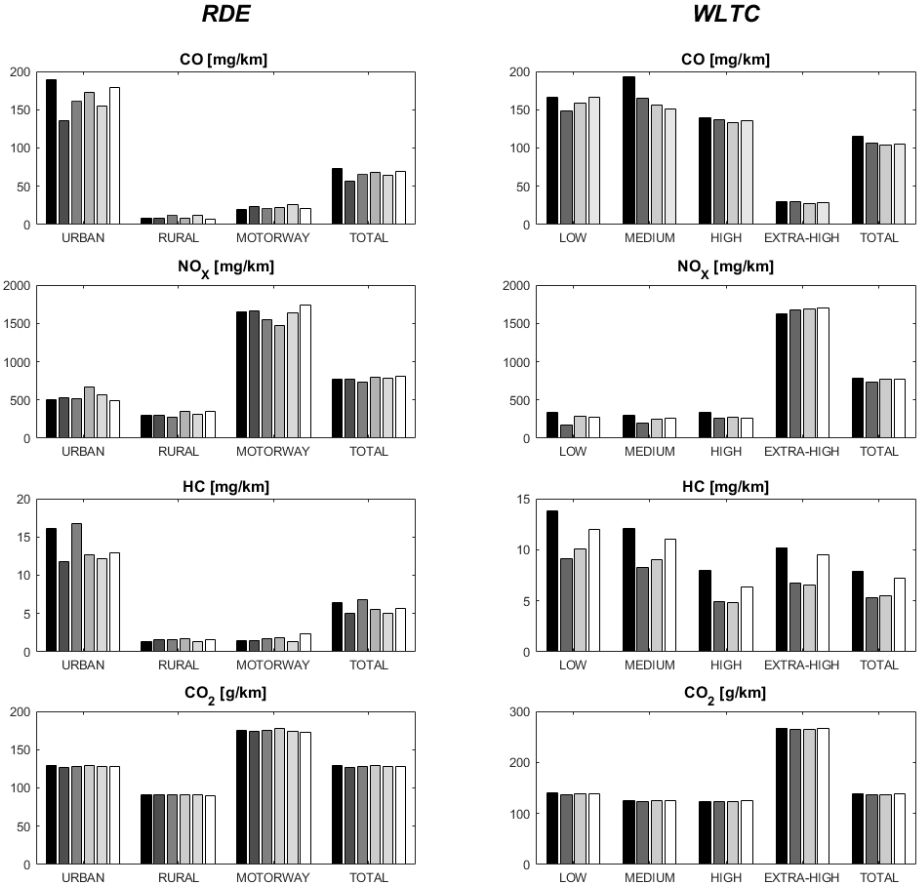

Figure 9: Test bench pollutant emissions.

As figure 9 shows, regardless of the cycle analysed, a very small differences between each repetition have been obtained. These data will be used in the following section to calculate the uncertainty of the measurements.

7. STATISTICAL ANALYSIS

This section presents the analysis of the dispersion in the results obtained in several repetitions of the tested driving cycles. Repeatability is defined by the National Institute of Standards and Technology (NIST) Guidelines for Evaluating and Expressing as [35]: ``Closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement´´. Repeatability may be expressed quantitatively in terms of the dispersion characteristics of the results. The following conditions are needed to evaluate repeatability:

- The same measurement procedure.
- The same observer.
- The same measuring instrument used under the same conditions.
- The same location.
- Repetition over a short period of time.

In order to identify anomalous results, the proposed methodology is split into two parts. The first part calculates the weighted average of the relative error of test variables. The relative error (∈) is weighted by means of the instantaneous variable measurement magnitude. The mathematical expression is shown in the equation 2, where the relative error is calculated by means of a Riemann sum.

$$\in = \frac{\int_0^T \bar{\beta}(t) * \bar{x}(t)\, dt}{\int_0^T \bar{x}(t)\, dt} \approx \frac{\sum_{i=0}^{i=n} \bar{\beta}(t) * \bar{x_\iota}}{\sum_{i=0}^{i=n} \bar{x_\iota}} \quad (2)$$

Where $\bar{\beta}$ is the instantaneous average relative error of each variable, $\bar{x}$ means the instantaneous measured average of each parameter, and n is the number of data points in a test. Both of them have been obtained from the average of several repetitions of the equivalent tests. In WLTC sampling frequency is 10Hz as long as in RDE is 1Hz (as imposed by the RDE regulation). Both acquisition frequencies fulfil sufficiently with the Nyquist-Shannon Theorem. Figure 10 shows one of the most transient part of RDE cycle, where the measured emissions somehow behave as a sinusoidal wave. The theorem stablish that the acquisition frequency must be at least twice the frequency of the phenome. In this example the "wave" frequency is about 0,1Hz, what forces the acquisition frequency to be bigger than 0,2 Hz. Acquisition at 1 Hz is higher enough to complying with the Nyquist-Shannon Theorem.

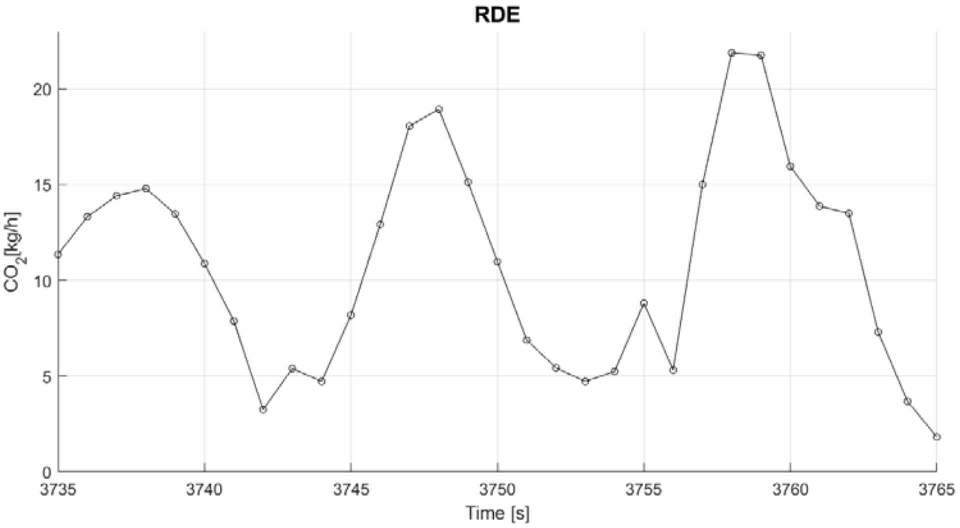

Figure 10: CO$_2$ emissions frequency.

Equation 3 shows as how β is calculated.

$$\bar{\beta} = \frac{1}{m} * \int_{j=0}^{j=m} \alpha_j \quad (3)$$

Parameter m means the number of test repetitions. Parameter α is the instantaneous relative error of each test repetition that can be calculated with the equation 4:

$$\alpha_j = \frac{|xj - \bar{x}|}{\bar{x}} \quad (4)$$

Where $\bar{x}$ is the parameter under study at the j test repetition. By combining equation 3 and 4, equation 5 can be obtained:

$$\in = \frac{\frac{1}{m}\sum_{i=0}^{i=n} \sum_{j=0}^{j=m} |x_{i,j} - \bar{x_\iota}|}{\sum_{i=0}^{i=n} \bar{x_\iota}} \quad (5)$$

This error calculation is a modification of the original definition of the Symmetric Mean Average Percentage Error (SMAPE) defined by Flores [36]. It shows how big is the dispersion of the tests.

In order to analyse the accuracy and uncertainty of the tests, the evolution of the next variables will be considered: Speed, Torque, Vehicle Speed, fuel mass low, exhaust mass flow, boost pressure, and turbine outlet temperature, during WLTC an RDE cycles.

Applying the equation 5 to the selected parameters, table 7 presents the errors obtained.

	RDE Error	WLTC Error
Exhaust mass flow	7,67%	3,79%
Speed	0,90%	0,33%
Torque	10,05%	4,68%
Vehicle Speed	0,92%	0,16%
Fuel Mass flow	14,45%	7,27%
Boost Pressure	1,89%	1,09%
Outlet temperature turbine	1,84%	1,56%

Table 7: RDE and WLTC errors.

As table 7 shows, excepting exhaust mass flow, torque and mass fuel Flow in RDE and mass fuel flow in WLTC, the other errors are below 5%. Only in case of WLTC an error higher than 5% was obtained related to the fuel mass flow.

In the cases where RDE errors are high, it is partially due to the high variation in a short time period. These errors are due to the difference between the measurement systems frequency and the acquisition frequency. The acquisition frequency applied was of 1Hz, and these variables can suffer relatively high variations in a second.

However, very small relative errors are obtained when the calculation is applied to the global values of the cycle. if the relative error is applied to the final mean values, very small values are obtained. It can be seen in table 8 where the relative errors are shown.

	RELATIVE ERROR			
	RDE			**WLTC**
Test	**Exhaust mass flow**	**Torque**	**Fuel mass flow**	**Fuel mass flow**
1	1,273%	0,356%	0,163%	1,158%
2	4,630%	0,688%	0,179%	0,911%
3	0,704%	0,395%	0,124%	0,268%
4	2,632%	0,296%	0,157%	0,021%
5	1,409%	0,352%	0,042%	
6	1,387%	0,594%	0,334%	

Table 8: RDE and WLTC relative errors.

Once these previous variables have been analysed, the second part consist of analysing the pollutant emission measurement. Provided that emissions naturally show higher dispersion that the previously analysed variables, a specific analysis methodology has been used.

This analysis is based on cumulated emissions of each repetition. After quantifying them, the standard deviation was calculated using the equation 7:

- $$\sigma = \sqrt{\frac{\sum_{i=1}^{i=n} (\mu - x(i))^2}{m-1}} \qquad (6)$$

where m is the sample size, μ is the pollutant average, and $x(i)$ the values of each repetition.

Table 9 presents the data obtained from the cumulated pollutant emissions in both RDE and WLTC.

		RDE				WLTC			
		CO	**NO_X**	**HC**	**CO_2**	**CO**	**NO_X**	**HC**	**CO_2**
Average	***[g/cycle]***	4,58	53,701	0,396	8,881	2,48	17,76	0,15	3,195
Median	***[g/cycle]***	4,63	54,13	0,39	8,863	2,44	17,87	0,15	3,196
SK	***[%]***	1,05%	0,79%	2,83%	0,20%	1,97%	0,65%	2,05%	0,01%
Range	***[g/cycle]***	1,15	4,95	0,13	0,181	0,25	1,17	0,06	0,0363
σ	***[g/cycle]***	0,3591	1,6026	0,0411	0,0611	0,1023	0,4350	0,0258	0,0169

Table 9: RDE and WLTC statistical analysis.

A 95% of confidence interval has been considered as shows the equation (8), where m is the sample size, and t_{m-1} depends on the simple size, 6 for RDE and 4 for WLTC and according to a Student-t distribution is 2.57 and 3.18 respectively.

$$CI(95\%) = Average \pm t_{m-1} * \frac{\sigma}{\sqrt{m}} \quad (7)$$

In RDE case, the following errors are obtained for the pollutant emissions

- CO = 4,58 ± 0,376 g/cycle = 4,580 ± 8,23 % g/cycle
- NO_X = 53,701 ± 1,681 g/ cycle =53,701 ± 3,13% g/cycle
- THC = 0,396 1 ± 0,043 g/ cycle = 0,396 1 ± 10,88% g/cycle
- CO_2 = 8,881 ± 0,064 kg/ cycle= 8,880 ± 0,72% kg/cycle

And WLTC case:

- CO =2,48 ± 0,162 g/cycle=2,484 ± 6,55% g/cycle
- NO_X =17,76 ± 0,691 g/cycle=17,755 ± 3,90% g/cycle
- THC= 0,15 ± 0,041 g/cycle= 0,149 ± 27,40% g/cycle
- CO_2 =3,195 ± 0,02688 kg/cycle=3,195 ± 0,84% kg/cycle

Considering a 95% confidence interval, CO2 and NO_X emissions uncertainty enter within the uncertainty of the measurement system. The highest percentage of error is found in the HC for the WLTC cycle. Also, CO the error is relatively high. It is mainly due to the particularity of those substances, which are produced mostly during cold starts. At these moments, the after-treatment system may be in a different state and therefore it can work having different efficiencies, since the temperature of the test cell is not accurately controlled. Also, as shows the results obtained, THC emissions are very low when compared to other emissions. So, small variations can lead to large percentage differences. For this reason, the variation of THC emissions should not be given too much importance when analysing the results.

Another methodology to verify the repeatability would be using the current tolerances for the PEMS validation method established in the European Regulation. This consist of measuring the emissions in a WLTC cycle, using a PEMS and a CVS (Constant Volume Sampler), and obtain a difference between the two that is less of one of the two following tolerances:

- Absolute tolerance.
- Relative tolerance if this relative tolerance is greater than the absolute tolerance.

Table 10 presents the tolerances and the maximum difference between the values obtained in RDE. It can be confirmed as the obtained tolerances are within the range of absolute or relative tolerances.

	Permissible absolute tolerance	Result	Permissible relative tolerance	Result
	mg/km	*mg/km*	*%*	*%*
CO	150	**9,97**	15%	15,07%
NO_X	15	44,49	15%	**5,73%**
THC	15	**1,08**	15%	18,93%
CO_2	10.000	**1556,69**	10%	**1,21%**

Table 10: Comparison between errors obtained and PEMS regulative tolerances.

8. CONCLUSIONS

In this paper, the feasibility of an engine test cell for reproducing the real driving conditions has been analysed. A cycle performed using a common passenger car has been implemented in the test cell control software. WLTC was also implemented. Once the cycles were repeated for several times, data corresponding to the engine operating together with pollutant emissions has been statistically treated.

The errors obtained from the statistical study are minimal in both cycles. In case the RDE cycle with a duration of 96 minute very low errors have been calculated. In the case of NOx emissions, the error is 3,13% in Nitrogen Oxides what takes on special importance, considering the importance that NOx emissions have in the regulation (specially for diesel engines).

CO and THC emissions have a similar behaviour, with the highest uncertainties being found in these substances. But so far these emissions are not a concern for vehicle manufacturers due to the high efficiency of oxidation catalysts incorporated in all vehicles, complying with the with regulations without mayor problems.

Focusing on RDE emissions on a test bench, the uncertainties obtained are quite small compared to RDE carried out on the road, where large differences can be found. Even in some cases, these cycles cannot be considered due to their high variability or because they do not comply with the regulation as shows some abovementioned research papers [23, 24, 25].

Therefore, it is of great interest to carry out these types of cycles in a test cell, so they can be compared to each other. Using this methodology, multiples studies could be done as parametric studies modifying driving behaviour or engine controls, aftertreatment system, engine components, etc... The uncertainty obtained in these tests can be used to quantify more precisely the eventual reduction of polluting substances that may occur, solely due to the engine modifications.

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