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Additional Information

Effects of low pressure exhaust gas recirculation on regulated and unregulated gaseous emissions during NEDC in a light-duty diesel engine

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ABSTRACT

Regulated and unregulated gaseous emissions with high pressure and low pressure exhaust gas recirculation (EGR) system were tested in a 4-cylinder, light-duty diesel EURO IV engine typically used in European vehicles. Four different engine calibrations with the low pressure EGR system were studied. Regulated emissions of NO_X, CO, HC and CO_2 were measured for each configuration. Unburned Hydrocarbon Speciation, formaldehyde (HCHO), formic acid (HCOOH) and nitrous oxide (N_2O) were also measured in order to determine the maximum incremental reactivity (MIR) of the gaseous emissions. Pollutants were measured without the diesel oxidation catalyst (DOC) to gather data about raw emissions. When the low pressure EGR system was used, decreases in NO_X, N_2O and fuel consumption were observed and significant increases HC, CO and unregulated emissions. The potential of tropospheric ozone production were higher in all cases when the low pressure EGR was used.

1. INTRODUCTION

Actual and future regulation limits, will force diesel engine manufacturers to drastically reduce gaseous emissions: Nitrogen Oxides (NO_X), Total Hydrocarbons (THC), Carbon Monoxide (CO), and particle matter emissions (PM). Although after-treatment devices will certainly see great improvements in the future, new in-cylinder strategies are emerging to reduce NO_X emissions. The recirculation of exhaust gases into the engine intake (EGR) is a well-known and established in-cylinder technology to reduce NO_X emissions by lowering the oxygen content on the intake air and consequently decrease in combustion peak temperature [1-3].

Modern engines use high pressure EGR, in which the exhaust gas is taken directly from the exhaust manifold and combined with the fresh charge air immediately before entering the engine. Increasing the EGR rate and using EGR over a wider range of engine operating conditions can further reduce NO_X emissions, but conventional high pressure EGR systems are reaching their limits. Highly permeable and fouling resistant valves and coolers are required to achieve the higher EGR gas flow rates. In addition, higher boost pressure is necessary to ensure an adequate air supply, while at the same time the exhaust gas available to drive the turbine is reduced [4].

A potential solution for providing higher EGR rates is low pressure EGR. The entire exhaust gas volume passes through the turbine, diesel oxidation catalyst (DOC) and the diesel particle filter (DPF) then the EGR gas is extracted from the exhaust stream and aspirated by the compressor along with the fresh air. The EGR gas is therefore at a lower pressure when it is combined with the fresh air than in the high pressure EGR circuit. Numerous benefits have been claimed for low pressure EGR. For example there is more energy available to the turbine to power the compressor, so higher EGR rates may be attained compared to high pressure EGR [5]. On the other hand, this additional exhaust flow could cause a more rapid loading of the DPF if the engine-out particle emissions are not reduced. Other risks with low pressure EGR include compressor damage by water droplets and particles from exhaust components, and acidic condensation in the EGR cooler and the charge air cooler [4-7].

Low pressure EGR loops have already been studied by some researchers on light-duty diesel engine [8-9], but very few studies concern automotive high-speed direct injection (HSDI) diesel engines. Finally, it has been shown that the decrease in recirculated gases temperature can further reduce NO_X emissions [10-11] and results in an improved NO_X–PM trade-off [12].

On the other hand, the many studies of exhaust gases speciation is an indication of the increasing interest in this topic by the scientific community [13-17] as a result of recent epidemiological and toxicological research suggesting a relationship between exposure to exhaust emission gases and adverse health effects [18-21].

In this study a low pressure exhaust gas recirculation (LP EGR) systems, with different engine calibrations were investigated in a light-duty diesel engine under the New European Driving Cycle (NEDC). The aims of this study were to test the NEDC in an engine test cell in the loop approach. In addition, regulated and unregulated emissions were measured by the Fourier transform infrared spectroscopy (FTIR) method.

2. STRUCTURE OF THE EXPERIMENT

2.1. Engine

The engine used was a 2.0-litre HSDI, turbo-diesel engine for passenger vehicles that complies with EURO IV. The engine is fitted with high pressure fuel injection using the common-rail injection system, an intercooler, variable geometry turbocharger (VGT) and exhaust gas recirculation (EGR).

The series engine is equipped with a high pressure EGR system. It consists of a duct that guides part of the exhaust gas directly from the exhaust to the intake manifold. An electronic valve regulates the EGR flow from the air mass flow measurement, and an EGR cooler is placed upstream the EGR valve in order to prevent the valve electronics from reaching high temperatures which could affect their reliability.

An experimental low pressure EGR system has been added to the engine. Low pressure EGR, also known as long route EGR, consists of taking part of the exhaust gases from the DPF outlet and introducing them at the compressor inlet. As in the case of the high pressure architecture, a valve controls the flow through the low pressure EGR duct by using the air mass flow measurement. Also, an EGR cooler reduces compressor inlet temperatures, avoiding excessive temperatures that could damage the turbocharger. Since the pressure difference between DPF outlet and compressor inlet is not high enough to achieve the required EGR flow in many operating conditions, a valve downstream the EGR extraction is used to increase the pressure difference between exhaust and intake lines, thus allowing higher EGR rates. Of course, this backpressure increase involves higher pumping losses, increasing the

brake specific fuel consumption (BSFC). In this sense, the minimization of the pressure losses is a key criterion in the design of the low pressure EGR loop elements. A scheme of the engine layout with both high and low pressure EGR systems is shown in *Figure 1*.

Figure 1.

The layout particularities of both low pressure and high pressure EGR systems involve some noticeable differences in engine behavior when those architectures are used:

When high EGR rates are applied with the high pressure loop, a substantial part of the energy at the cylinders exhaust is redirected to their inlet, thus reducing the available energy at the turbine inlet, limiting the intake pressure and worsening dynamic performance. The coupling of the turbine and the high pressure EGR has been subject for an extensive literature [22-24]. In the case of the low pressure system, EGR and turbocharging are almost decoupled; nevertheless, due to the important distance between the EGR injection in the intake line and the cylinders, there is an important delay in the EGR rate that also damages transient behavior.

The introduction of the EGR before the compressor also allows the low pressure configuration to provide engine cylinders with a perfectly homogenized charge, thus differences in the amount of air and EGR that absorbs each cylinder are negligible. On the contrary, with the high pressure loop significant EGR variations between cylinders appear due to the short distance between the EGR junction and the cylinders, which prevents a suitable mixing.

Since the pressure difference between exhaust and intake manifolds is usually higher than the pressure difference between DPF outlet and compressor inlet, the low pressure EGR system does not allow achieving EGR rates as high as those obtained with the high pressure EGR architecture. Then, as far as the low pressure EGR architecture is concerned, a back pressure valve placed downstream the EGR extraction is required in order to increase the pressure difference between exhaust and intake lines, thus allowing higher EGR rates. However, the backpressure valve actuation involves an increase in exhaust pressure and then pumping losses that affects engine efficiency negatively [5, 25]. Therefore, the backpressure valve is only used for increasing the EGR rate once EGR valve becomes fully open.

Finally, since the low pressure EGR gas is taken from the DPF outlet it is much colder than the gas extracted from the turbine inlet in the high pressure approach. In addition, the low pressure EGR gas passes through both the EGR cooler and the intake charge cooler. Therefore the intake temperature reached with a low pressure EGR system is significantly lower than that obtained with a high pressure EGR loop. A mean intake temperature of 60ºC is achieved during the NEDC with the high pressure EGR architecture, while 40ºC is a representative mean temperature of the intake gas with the low pressure EGR loop. In addition to the effects of such a lower intake temperature on combustion, the lower intake temperature also involves a higher intake gas density and therefore a larger amount of gas admitted by cylinders.

2.2. Engine calibration and tested strategies

The mass admitted by the engine cylinders contains both fresh air and EGR, so there is a strong coupling between these flows. In current diesel engines, the EGR valve is used to control air mass flow and therefore EGR rate in a closed loop strategy, taking the measured air mass flow as a feedback variable. A reference air mass flow, calibrated in steady tests, is implemented in ECU maps as a function of engine speed and injected fuel quantity. Then, the EGR valve position is set by means of a PID controller from the difference between the set point and the measured air mass flow. Since for a given engine speed and fuel demands, the mass admitted by the engine is higher with the low pressure

EGR system (due to the lower intake temperature and higher density) for a given air mass flow demand, the engine with low pressure EGR can absorb an additional amount of EGR. This behavior is fully described in [25]. The additional amount of EGR gas has important effects on engine performance and emissions.

As far as the original engine has not a low pressure EGR system, the original engine calibration is optimized for using a high pressure EGR system. Accordingly, while the high pressure architecture was tested in its base line configuration (HP EGR), four different calibrations were tested with the low pressure EGR loop in order to adapt the engine calibration to the low pressure EGR features:

- LPEGR: The low pressure EGR system was employed with the engine baseline calibration to isolate the effects of the EGR layout on engine performance.
- LP EGR$_{(I)}$: The increase in the EGR rate promoted by the lower intake temperature achieved with the low pressure EGR system involves a delay in the combustion that despite reducing NOx emissions can damage soot, HC emissions and also fuel economy [24]. To avoid those negative effects the engine calibration was modified, advancing 2º in the whole engine map with respect the original calibration. Therefore the comparison between results obtained with this strategy and LPEGR allows analyzing the effect of the start of injection on engine performance and emissions.
- LP EGR$_{(L)}$: This strategy consists on increasing the air mass flow demands in order to reduce the EGR rate. In this sense, the air mass flow set points included in the original ECU calibration were increased in a 5%. Then, the comparison between results obtained with this strategy and LPEGR allows analyzing the effect of the EGR rate on engine performance and emissions.
- LP EGR$_{(O)}$: Finally, the last strategy combines both LP EGR$_{(I)}$ and LP EGR$_{(L)}$ approaches advancing the start of injection in 2º and increasing the air mass flow demand in a 5% simultaneously.

2.3. General instrumentation

The engine was installed in a test cell equipped with a variable frequency fast response asynchronous dynamometer manufactured by Horiba-ATS®, which allows controlling online the engine speed and load by STARS® software that programs the type of the vehicle driving cycle. By means of this software, and taking into account the vehicle features, and a current driver skills the NEDC cycle is programmed as a time sequence of gears and vehicle speeds. In order to possible modification of any of the engine parameters, the Engine Control Unit (ECU) is totally opened and the engine settings maps can be recalibrated with the ETAS INCA® software.

Fuel consumption was determined by two systems. The first consists of a fuel gravimetric system with an AVL® 733S Dynamic Fuel Meter. The measurement device consists of a measuring vessel filled with the fuel and suspended on a balance system. Fuel consumption values are obtained by calculating the vessel's weight loss over time. Since the response time of this system might possibly be too long for this study, the fuel consumption signal provided by the ECU was calibrated in steady state. After calibration, the ECU was used as a second fuel consumption measuring system as proposed in [26].

The Sensyflow P Sensycon hot-plate anemometer system was used to measure the flow rate of the intake air mass. The measurement range of the anemometer is 0-720 $kg \cdot h^{-1}$.

Engine gaseous emissions were analyzed without exhaust after-treatment system (Diesel Oxidation Catalyst). Emissions (CO, CO_2, NO, NO_2, N_2O, HCHO, HCOOH, C_4H_6, C_6H_6, C_7H_8 and other compounds) were directly measured in the exhaust pipe by a HORIBA® MEXA–6000FT engine exhaust gas analyser. The exhaust line was connected directly to the equipment by a pipe whose wall

temperature was maintained at 113º C in order to avoid hydrocarbon condensation. Firstly, the system obtains an interferogram using the Michelson interferometer and the interferogram is then converted to the infrared absorption spectrum by Fast Fourier Transform (FFT) whilst a multivariable analysis enables the concentration analyses of different components to be combined in a single analysis. Since the unique spectrum of many compounds is in the infrared range, this method is used for quantitative and qualitative analysis [27].

Since CO_2 measurement is the method most widely used to determine the EGR rate intake and exhaust CO_2 concentration are also measured by a HORIBA® MEXA–7100DEGR. CO_2 concentrations are measured by means of NDIR analyzers. As can be found in literature, EGR rate can be calculated from CO_2 concentration in intake and exhaust manifolds by means of the following equation:

$$EGR (\%) = \frac{[CO_2]_{intake} - [CO_2]_{atm}}{[CO_2]_{exhaust} - [CO_2]_{atm}} \times 100 \qquad \text{Eq. (1)}$$

High accuracy transducers are used in order to assure suitable measurements of both temperature and pressure suitably located in the intake, exhaust and cooling system zones.

2.4. Driving cycle and measurement protocol

Measurement strategies are necessary in a realm like engine emission experimental research due to the many dispersion factors able to introduce variability. The European directive 91/441/EEC defining NEDC contains no explicit procedure for preconditioning the engine before running a transient test. The only specification in current European emission legislation as regards the performance of transient tests is that ambient temperatures must be above 20º C. It must be remembered that these tests were performed for the purpose of research, not regulations. With the purpose to achieve confident and repetitive measurements during the NEDC cycle, the test procedure developed in [28] was adopted in this work.

Despite the on-going development of enhanced exhaust gas analysers, there are considerable difficulties with emission measurement that must be taken into account when conducting transient tests. The main problem is that exhaust gas analysers usually have longer response times than other engine transducers. Pollutant emission signals are, therefore, slightly delayed in comparison with the other engine parameters. Since exhaust gas analysers measure pollutant concentration, exhaust mass flow must be determined in order to calculate the instantaneous mass of pollutants emitted.

The synchronization of exhaust mass flow and pollutant emission measurement devices is, therefore, critical. The synchronizing method adopted in this study is described in-depth in the [28].

Then, the impact of the different configuration of low pressure EGR on pollutant emissions will be evaluated through the comparison with the results obtained in preliminary tests with high pressure EGR. In the following sections, the pollutants emitted during the NEDC cycle with LP EGR, LP EGR$_{(I)}$, LP EGR$_{(L)}$, and LP EGR$_{(O)}$ will be compared. Despite the emission levels will be different; this type of analysis is reliable, because similar global trends are expected in the instantaneous emissions for all tested configurations

3. RESULTS AND DISCUSSIONS

3.1. Error analysis

In order to minimize as possible errors in the experiments, all sensors were calibrated following rigorously the calibration procedures recommended by the sensor manufacturers. **Table 1** summarizes the accuracy of the instrumentation used in this work determined by the calibration. The propagation of the random errors from independent variables – which are measured with the calibrated sensors – toward results as instantaneous gaseous emission, fuel mass and air mass flow was evaluated using the first order approach as

$$\sigma_f(x_1, x_2, \dots, x_n) = \sqrt{\sum_l^n \left(\frac{\partial f}{\partial x_i}\bigg|_{\overline{x_i}} \sigma x_i \right)^2} \qquad \text{Eq. (2)}$$

Where σ is the standard deviation and $\overline{x_i}$ indicates the mean value of the *i-th* independent variable. By means of this error analysis, the accuracy of the instantaneous emissions and fuel consumption was estimated to be within 2%.

Table 1.

3.2. Engine parameters

In this section, the main results concerning engine performance will be presented. Since both EGR configurations with the different calibrations allow following the vehicle speed defined by the NEDC properly, the main performance parameter is the fuel consumption and CO_2 emitted by the engine during the test.

In this sense, **Figure 2** shows the evolution of the fuel consumption during the NEDC, since the same fuel composition was employed in the five tests; the evolution of the CO_2 emitted follows the same pattern. Regardless the EGR system employed, it can be observed that the fuel consumption during the first ECE is higher than in the other ECEs. In fact, as the cycle evolves, the fuel consumption is progressively reduced. The reason for the reduction in the fuel consumption is that as the cycle evolves the engine warms up and engine losses decrease due to lower friction losses and temperature gradients. Also, it can be observed that the most part of the fuel is consumed in the last phase of the NEDC, during extra-urban driving conditions (EUDC) where higher power demands are achieved due to aerodynamics and inertial factors become more important.

Figure 2.

Regarding the effect of the EGR layout, the main thing which is observable is that with the series calibration, the fuel consumption with the low pressure architecture is higher than with the high pressure system, 613g per cycle consumed with the low pressure lay out in front of 590g with the High Pressure system. It can be observed that this difference is due to an increase in the fuel consumption during the steady state phases. The negative effect of the higher EGR rate during those phases and also the increase in the backpressure with the low pressure system involve higher pumping losses and lower engine efficiency. Since NO_X emissions with the low pressure architecture are noticeably lower than those obtained with the high pressure layout, the start of injection can be advanced in order to recover the power losses, even at the expense of eliminating the NO_X advantage. With this strategy, the fuel consumption can be strongly reduced to 572g per cycle, nevertheless, combustion noise and NO_X emissions would be increased. Optimizing the back-pressure valve actuation to reduce pressure losses also increases efficiency, reducing the fuel consumption to 576g per cycle without appreciable NO_X increase. Finally, combining the previous strategies, the fuel consumption is reduced to 543g per cycle

keeping a non-neglecting NO_X advantage. **Figure 3** show a resume of the CO_2 emitted and the fuel consumed with the different strategies, showing that CO_2 emissions and fuel consumption are strongly correlated.

Figure 3.

3.2.Regulated emissions

In this section the results of pollutant emissions are going to be discussed, to better show the effect of the low pressure EGR (LP EGR) and the different engine calibrations (LP $EGR_{(I)}$, LP $EGR_{(L)}$, LP $EGR_{(O)}$), over the emissions of nitrogen oxides (NO_X), carbon monoxide (CO) and unburned hydrocarbons (THC).

3.2.1. NO_X emissions

Figure 4 shows the evolution of NO_X emissions, clearly demonstrates that most NO_X is emitted during the extra-urban driving cycle (EUDC) phase. As expected, NO_X emissions decreasing a 5% with the use of low pressure EGR (LP EGR) this is the result of a lower intake manifold temperature, which provides a higher gas density. Although the compressor outlet temperature of the air-EGR mixture is higher than when fresh air alone is compressed, the entire mixture is cooled in the cooler, in the high pressure EGR (HP EGR) configuration the EGR combines with the air downstream of the cooler, leading to a higher mixed gas temperature at the intake manifold.

Figure 4.

With the modification in the start of the injection (LP $EGR_{(I)}$) the NO_X was increased due to the raise on the combustion temperature, this increase was of 3% in comparison with the NO_X emissions of the HP EGR; in the cases of air loop optimization (LP $EGR_{(L)}$) the large reduction of the NO_X was founded. With this engine calibration the effects of decrease on the intake temperature and decrease on the oxygen availability reduces the NO_X emissions in 21%; and by means the combination of the above configurations (LP $EGR_{(O)}$), the reduction in the total NO_X emissions can be achieved in 10%.

Figure 5.

3.2.2. CO emissions

During test with the LP EGR system, the highest EGR rate could affect the ignition behaviour of fuel significantly. The increase of the EGR rates decelerates the reaction rates of the mixture and, thus, produced lower temperatures. In such a case, the flame propagation may not be sustained with relatively leaner mixtures. This could possibly increase the carbon monoxide emissions in the exhaust [10].

Figure 6.

Additionally the reduced availability of oxygen in the combustion chamber and a lower intake temperature increased CO levels (**Figure 6**), 1.6 times higher with the use of LP $EGR_{(I)}$, and 3.0 times higher with the LP $EGR_{(L)}$ configuration compared with the use HP EGR, in cases of LP EGR and LP $EGR_{(O)}$, the increase was 2.6 times and 2.8, respectively, it should be noted that the measurement are made upstream of the after treatment device (Diesel Oxidation Catalyst). Since oxidizing catalysts drastically reduce CO emissions, the large differences in emissions are reduced after the catalyst [29-30].

3.2.1. THC emissions

Hydrocarbons emissions are the result of incomplete combustion in which some hydrocarbons are not fully oxidized. In this respect, HC emissions are closely linked to CO emissions since they are both caused by low quality combustion. The effect of LP EGR on HC emissions is, therefore, similar to its effect on CO emissions as can be observed in **Figure 7**. As a result, increases of 1.3 times, 1.1 times, 1.7 times, and 1.6 times were observed for LP EGR, LP EGR$_{(I)}$, LP EGR$_{(L)}$, and LP EGR$_{(O)}$ in comparison with HP EGR.

Figure 7.

It is common knowledge that the reaction between nitrogen oxides (NO_X) and some total hydrocarbons (THC) in sunlight produces photochemical smog. Since not all THCs react with NO_X in the same way, THC speciation is needed in order to determine the potential of these gases to produce ozone precursors. One way of detecting photochemical smog is to determine the reactivity of each THC with NO_X according to different scales such as the Maximum Incremental Reactivity (MIR) scale developed by Carter (used by the California Air Resources Board and the US.EPA [31]) and the Photochemical Ozone Creation Potential (POCP) scale [32]. These scales are used to determine the quantity of tropospheric ozone: the parameter that determines the level of harmful exhaust gases produced by different engine calibrations.

With the traditional HC measurement system it is not possible to detect the levels of the different compounds in hydrocarbon emissions. In order to understand the nature of these compounds better, exhaust hydrocarbons from each test were speciated.

3.3. Unregulated emissions

3.3.1. Hydrocarbon speciation

The most comprehensive analysis of hydrocarbons is called hydrocarbon speciation. In this analysis, hydrocarbon levels from C_1 to C_7 (Methane (CH_4) to Toluene (C_7H_8)) are quantified. The results from hydrocarbon speciation analysis are used to compare the relative potential for hydrocarbon emissions from the various fuels to form photochemical smog.

Figure 8.

Figure 8 shows the THC composition of all used configurations. This is the composition of the total hydrocarbon emissions shared in **Figure 7**. The changes in hydrocarbon structures can be explained by three phenomena that occur in different pressure and temperature conditions [16, 17, 29] i.e.:

✓ Cracking: the division of a long-chain carbon molecule into two small molecules (paraffin and olefin) or two paraffin molecules
✓ Polymerization: a combination of two olefin molecules to form one larger olefin molecule.
✓ Reformed: the catalytic conversion of paraffinic or naphthenic molecules into aromatic molecules by pyrolysis.

Thermal cracking affects all long-chain paraffin's, this process involves a mechanism in which bonds are broken and form radicals, leading subsequently to pairs of paraffin's and olefins as the chains are shortened [16]. Olefins have a greater tendency to split than paraffin's, hence the high ethylene (C_2H_4) levels in exhaust gases in comparison with light paraffin such as propene (C_3H_6). Ethylene is an

interesting compound to analyse due to its high maximum incremental reactivity (MIR: 9.08). So iso-butene (C_4H_8), which has the highest incremental reactivity of all the compounds, considered in this study (MIR: 10.29). The iso-butene variations in different NEDC phases shown in **Figures 9**, demonstrate that the highest levels of hydrocarbons occur during the ECE phase where operating conditions are low load and low speed. In such operating conditions, the combustion process is less efficient due to the low fuel/air ratio (ϕ), resulting in higher levels of said hydrocarbons.

Also as the cycle evolves and the engine temperature becomes stable, the emissions pattern becomes periodic. It means that, the differences between consecutive ECE cycles are reduced progressively and negligible differences between third and fourth ECE cycles are observed in comparison with the first and second ECE cycle (**Figure 9**).

Figure 9.

1,3 butadiene (C_4H_6) is an interesting compound because the increase of the emissions with the use of the different LP EGR configurations and for its high incremental reactivity (MIR: 7.7). This compound is not found in the fuel, which means that is it formed by the thermal cracking processes. Butadiene is usually produced by olefin cracking, although it can also be produced by double or multiple paraffin cracking. Its appearance in exhaust gases is explained by the high stability conferred upon it by its two double conjugated bonds.

Figure 10.

Benzene (C_6H_6) and Toluene (C_7H_8) (the compounds of most concern due to their supposedly carcinogenic effects), have lower atmospheric reactivity MIR: 0.81 and MIR: 3.97 respectively) Aromatic hydrocarbons in general (toluene, xylenes, ethyl benzene and particularly benzene) can be also be generated from paraffinic hydrocarbons C_6 and C_7 by isomerisation or the reforming process. Benzene variations shown in **Figures 10**, demonstrate that the highest peaks of emissions occur during the deceleration phase, also the high emissions levels at steady speed are even clearer in the ECE cycle. Aromatic hydrocarbons are difficult to remove by oxidation catalysis [33], so the HP EGR configuration is at an advantage in this respect in comparison with the LP EGR configurations.

Finally, methane (CH_4) is a greenhouse gas that remains in the atmosphere for approximately 9-15 years. Methane is over 20 times more effective in trapping heat in the atmosphere than carbon dioxide (CO_2) over a 100 year period [34]. Methane can be generated by the thermal cracking of both paraffinic and olefin hydrocarbons. The atmospheric reactivity of methane is lower than the other compounds analysed (MIR: 0.01). The use of EGR LP produced CH_4 emissions 50% higher than HP EGR configurations, whilst EGR $LP_{(I)}$, EGR $LP_{(L)}$ and EGR $LP_{(O)}$ configurations, caused an increases of 52%, 43% and 47% respectively.

In general, hydrocarbons speciation show similar trends for all compounds, as commented before, the raise in EGR rate leads to an increase on HC and CO emissions.

3.3.2. *Formic acid and formaldehyde emissions*

Formaldehyde and formic acid are the main oxygenated compounds formed in the combustion [35]. HCHO is also the main intermediate during the oxidation process. It is the last stable intermediate compound before coming CO and plays the role of terminator of the chain reaction mechanics by decreasing OH [36-37]. Total formaldehyde emissions are shown in **Figure 11** emissions follow a trend similar to THC emissions, this study recorded formaldehyde emissions 5 to 9 times higher when different configurations of the LP EGR compared with the HP EGR.

Figure 11.

Formic acid formation mechanism cannot be found in the literature yet; general paths must be explored first. It must be noticed that there is no proof whether exhaust organic acids are formed during the combustion process or they are products of post oxidation of active species or they come from the recombination of radicals during the cooling phase of exhaust gases. One possible pathway for acids formation is the further oxidation of aldehydes, known products of hydrocarbons oxidation. Similar tendencies of HCHO have been found for the HCOOH emission (**Figure 12**), the increase in the HCOOH emissions ranges from 2 times to 9 times higher when using LP EGR.

Figure 12.

3.3.3. Nitrous oxide emission

Nitrous oxide (N_2O) is one of the most important active trace gases in the atmosphere, due to its long atmospheric lifetime (approximately 120 years) and heat trapping effects which are, about 310 times higher than carbon dioxide on a per molecule basis. Also some studies suggests that N_2O emissions currently is the single most important ozone depleting substance emissions and is expected to remain the largest throughout the twenty one century.

The production of N_2O is strongly affected by the O_2 concentration. In the combustion process, N_2O is formed via NO [1, 38]. The concentration of this specie is affected mainly by in-cylinder temperature as with the NO_X formation. However, under conditions where NO_X are formed N_2O concentrations is controlled by the equivalence ratio rather than in-cylinder temperature [39]

Figure 13.

Figure 13 show the accumulative nitrous oxide concentration in the exhaust gas as a function of the time in the NEDC, with the use of LP EGR system a reduction of 40% in the total N_2O emissions can be found, in the cases of LP EGR(I), LP EGR(L) and LP EGR(O), the reduction were 48%, 57% and 52% respectively compared with the use of HP EGR.

3.3.4. Maximum Incremental Reactivity

The MIR (Maximum Incremental Reactivity) in the exhaust gases was measured. This parameter is obtained from the carbon monoxide (CO), hydrocarbons speciation, formaldehyde (HCHO) and formic acid (HCOOH), and indicates the ozone (O_3) arising from the production of photochemical smog in the atmosphere. **Figure 14** shows how MIR increases from 0.967 g·km^{-1} for HP EGR to 1.281 g·km^{-1} for LP EGR. The exhaust gases for LP EGR(I) produce 1.174 g·km^{-1}, 1.209 g·km^{-1} for LP EGR(L), and 1.226 g·km^{-1} LP EGR(O).

Figure 14.

4. CONCLUSIONS

This paper sets forth the findings of a study of regulated and unregulated gaseous emissions in a light-duty diesel engine during NEDC using high and low pressure exhaust gas recirculation with different engine calibrations. The main conclusions of the study are as follows:

- Fuel consumption increases with the use of low pressure EGR without engine calibration modifications by the increase in the pumping losses and the lower engine efficiency but with the optimization of the back pressure valve and the start of the injection can be achieved a reduction in total fuel consumption. A similar pattern was observed in CO_2 emissions with a decrease with the EGR $LP_{(O)}$ configuration, in comparison with HP EGR.
- Without changing the engine calibration, less NO_X is produced with the low pressure EGR system than with the high pressure EGR system. Nevertheless, a thorough engine recalibration would be necessary to fully benefit from the system
- The study found a total NO_X emissions reduction keeping low fuel consumption by changing the engine calibration with the low pressure EGR system
- Carbon Monoxide and Total Hydrocarbons emissions are increase when low pressure EGR system is used due to the deceleration of the reaction rates of the mixtures and the lower combustion temperatures.
- The trends in speciated hydrocarbon emissions and THC emissions suggest that these molecules are produced mainly by cracking and reforming.
- The use of low pressure EGR increases these emissions to significant levels.
- Formaldehyde and Formic acid emissions increase with low pressure EGR system, similar trends to the THC can be found.
- Nitrous Oxide (N_2O) emissions decrease with the low pressure EGR system for all engine calibrations.
- Maximum Incremental Reactivity was used to analyse the potential of exhaust gases to create tropospheric ozone. An increase in the potential ozone production was observed when low pressure EGR system was used.

5. DEFINITIONS/ABREVIATIONS

BSFC: Brake Specific Fuel Consumption

C_6H_6: Benzene

CO: Carbon Monoxide

CO_2: Carbon Dioxide

DOC: Diesel Oxidation Catalyst

DPF: Diesel Particle Filter

ECE: Urban Driving Conditions

EGR: Exhaust Gas Recirculation

EUDC: Extra Urban Driving Cycle

FTIR: Fourier transforms infrared spectroscopy

HC: Hydrocarbons

HCHO: Formaldehyde

HCOOH: Formic Acid

HP: High Pressure

HSDI: High Speed Direct Injection

iso-C$_4$H$_8$: iso-butene

LP: Low Pressure

MIR: Maximum Incremental Reactivity

N$_2$O: Nitrous Oxide

NEDC: New European Driving Cycle

NO$_X$: Nitrogen Oxides

PM: Particulate Matter

VGT: Variable Geometry Turbocharger

6. REFERENCES

[1]   Heywood, JB. *Internal Combustion Engine Fundamentals.* New York: McGraw-Hill; 1988.

[2]   Zheng M, Reader GT, Hawley JG. "Diesel engine exhaust gas recirculation - a review on advanced and novel concepts." *Energy Convers. Manage.* 2004;44:883-900.

[3]   Torregrosa AJ, Olmeda P, Martin J, Degraeuwe B. "Experiments on the influence of inlet charge and coolant temperature on performance and emissions of a DI diesel engine." *Exp. Therm Fluid Sci.* 2006;30:633-41.

[4]   Moroz, S, G Bourgoin, J M Luján, and B Pla. "A 2.0 litre Diesel Engine with Low Pressure Exhaust Gas Recirculation and Advanced Cooling System." *Diesel Engine Conference, Proceedings of the SIA 2008 Conference.* Rouen, France, 2008.

[5]   Moroz, S, G Bourgoin, J M Luján, and B Pla. "Advanced Cooling Systems for Low Pressure Exhaust Gas Recirculation in a Turbocharged Diesel Passenger Car Engine." *FISITA World Automotive Congress.* Munich, Germany, 2008.

[6] Van Aken M, Willens F, Jong DJ. "Appliance of High EGR Rated With a Short and Long Route EGR System on a Heavy Duty Diesel Engine." *SAE paper 2007-01-0906*, Warrendale, PA: Society of Automotive Engineers Inc.; 2007.

[7] Beatrice C, Avolio G, Del Giacomo Ch, Lazzaro M. "The Effect of "Clean and Cold" EGR on the Improvement of Low Temperature Combustion Performance in a Single Cylinder Research Diesel Engine." *SAE Paper 2008-01-06-50*, Warrendale, PA: Society of Automotive Engineers Inc.; 2008.

[8] Maiboom A, Tauzia X, Hétet J-F. "Influence of high rates of supplemental cooled EGR on NO_X and PM emissions of an automotive HSDI diesel engine using an LP EGR loop." *Int. J. Energy Res.* 2008;32:1383-98.

[9] Maiboom A, Tauzia X, Hétet J-F. "Experimental study of various effects of exhaust gas recirculation (EGR) on combustion and emissions of an automotive direct injection diesel engine." *Energy* 2008;33:22-34.

[10] Abu-Hamdeh NH. "Effect of cooling the recirculated exhaust gases on diesel engine emissions." *Energy Convers. Manage.* 2003;44:3113-24.

[11] Pickett, L M, and C A Idicheria. "Effects of ambient density and temperature on soot formation under high-EGR conditions." *12th Annual Diesel Engine Emissions Reduction Conference.* Detroit USA, 2006.

[12] Hountalas DT, Mavropoulos GC, Binder KB. "Effect of exhaust gas recirculation (EGR) temperature for various EGR rates on heavy duty DI diesel engine performance and emissions." *Energy* 2008;33(2):272-83.

[13] Wallington TJ, Kaise EW, and Farrell JT. "Automotive fuels and internal combustion engines: a chemical perspective." *Roy Soc Chem* 2006;35:335-47.

[14] Ballesteros R, Hénandez J, Lyons L, Cabañas B, Tapia A. "Speciation of the semivolatile hydrocarbon engine emissions from sunflower-oil biodiesel." *Fuel* 87 (2008;87:1835-43.

[15] Di Y, Cheung CS, Huang Z. "Experimental investigation on regulated and unregulated emissions of a diesel engine fueled with ultra-low sulfuer diesel fuel blended with biodiesel from waste cooking oil." *Sci. Total Environ.* 2009;407:835-46.

[16] Payri F, Bermúdez V, Tormos B, Linares WG. "Hydrocarbon emissions speciation in diesel and biodiesel exhausts." *Atmos. Environ.* 2009;43:1273-9.

[17] Bermúdez V, Lújan JM, Pla B, Linares WG. "Comparative study of regulated and unregulated gaseous emissions during NEDC in a light-duty diesel engine fuelled with Fischer Tropsch and Biodiesel fuels." *Biomass Bioenergy* 2011;35:789-98.

[18] Brookes P, Duncan M. "Carcinogenic Hydrocarbons and Human Cells in Culture." *Nature* 1971;234:40-3.

[19] Cohen, A J, and W P Higgins. "Health effects of Diesel Exhaust: Epidemiology. In: Diesel exhaust: A Critical Analysis of Emissions, Exposure, and Health Effects." Health Effects Institute, A special report of the Institute's Diesel Work Group, Cambridge, 1995.

[20] Watts, W F. "Assessment of occupational exposure to diesel emissions. In: Diesel exhaust: a critical analysis of emissions, exposure, health effects." A special report of the Institute's Diesel Work Group, Health Effects Institute, Cambridge, 1995.

[21]   De Rui A, De Assuncao JV, Pesquero CR. "Emissions of polycyclic aromatic hydrocarbons from light-duty diesel vehicle exhaust." *Atmos. Environ.* 2004;38:1631-40.

[22]   Stefanopoulou AG, Kolmanovsky I, Freudenberg JS. "Control of Variable Geometry Turbocharged Diesel Engines for Reduced Emissions." *IEEE Trans. Control Syst. Technol.* 1999;8:733-45.

[23]   Ammann M, Fekete NP, Guzzella C, Glattfelder AH. "Model-based control of the VGT and EGR in a turbocharged common-rail Diesel engine: Theory and passenger car implementation." *SAE paper 2003-01-0357*, Warrendale, PA: Society of Automotive Engineers Inc.;2003.

[24]   Jacobs T, Assanis D, Filipi Z. "The Impact of Exhaust Gas Recirculation on Performance and Emissions of a Heavy-Duty Diesel Engine." *SAE paper 2003-01-1068*, Warrendale, PA: Society of Automotive Engineers Inc.;2003.

[25]   Lújan, J M, B Pla, S Moroz, and G Bourgoin. "Effect of Low Pressure EGR on gas exchange processes and turbocharging of a HSDI engine." *THIESEL 2008 conference on thermo and fluid dynamic processes in diesel engines.* Valencia, Spain, 2008.

[26]   Broatch, A, J M Lújan, J R Serrano, and B Pla. "Pollutants instantaneous measurement and data analysis of engine-in-the-loop tests." *THIESEL 2006 conference on thermo and fluid dynamic processes in diesel engines* . Valencia, Spain , 2006.

[27]   Kawarabayashi, S, Y Yamagishi, H Kachi, and S Kobayashi. "Measurement of Vehicle emissions with Fourier Transform Infrared (FTIR) method." *Proc Comodia* 1990;90:365-9.

[28]   Arregle J, Bermúdez V, Serrano JR, Fuentes E. "Procedure for engine transient cycle emissions testing in real time." *Exp. Therm Fluid Sci.* 2006;30:485-96.

[29]   Baerns M. *Basic principles in applied catalysis.* In: F. Schmidt, Editor. *The importance of Catalysis in the Chemical and Non-Chemical Industry.* New York: Springer-Verlag; 2004.

[30]   Heck R, Farrauto R. *Catalytic Air Pollution Control.* New York: International Thompson Publishing; 1995.

[31]   California code of regulations. "Article 1, Tables of Maximum Incremental Reactivity (MIR)." 2001, 94-7000-94701.

[32]   Derwent RG, Jenkin M, Saunders S. "Photochemical ozone creation potentials for a large number of reactive hydrocarbons under European conditions." *Atmos. Environ.* 1996;30:181-99.

[33]   Li T, Izumi H, Shudo T, Ogawa H. "Characteristics of unregulated toxic emissions from ultra-high EGR low temperature diesel combustion and effects of exhaust catalyst." *JSME Trans. B* 2007;73:1129-34.

[34]   U.S. Environmental Protection Agency. 2006. Inventory of U.S. greenhouse gas emissions and sinks: 1990-2004. EPA/430/R-06/002. Washington, DC.

[35]   Peng CY, Yang HH, Lan CH, and Chien SM. "Effect of the biodiesel blend fuel on aldehyde emission from diesel engine exhaust." *Atmos. Environ*. 2008;42:906-15.

[36]   Zervas E, Montagne X, Lahye J. "Emissions of alcohols and carbonyl compounds from a spark ignition engine. Influence of fuel and air/fuel equivalence ratio." *Environ. Sci. Technol.* 2002;36:2414-21.

[37]   Takada Y, Yoshimura F, Ohga Y, Kusada J, Daisho Y. "Experimental study on unregulated emissions characteristics of turbocharged DI diesel engine with common rail fuel injection system." *SAE Paper 2003-01-3158*, Warrendale, PA: Society of Automotive Engineers Inc.;2003.

[38]   Gardiner Jr WC. *Gas-Phase Combustion Chemistry* . New York: Springer-Verlag; 2000.

[39]   Yamada H, Misawa K, Suzuki D, Tanaka K, Matsumoto J, Masaaki F, et al. "Detailed analysis of diesel vehicle exhaust emissions: Nitrogen oxides, hydrocarbons and particle size distributions." *Proc. Combust. Inst.* 2011;33:2895-902.