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Study of implementation of hybrid EGR during transient operations on diesel engine to reduce an instantaneous NOx emissions measured with a fast emission measurement system.

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Abstract

Knowing the importance of EGR, to control the emissions from internal combustion engines and to cope with future emissions standards, it is necessary to investigate the influence of EGR on diesel engines. Specially, the need of studying transient operations, playing vital role in newly developed driving cycles like WLTP and RDE is getting prominent. This study consists a utilization of high pressure and low pressure exhaust gases with different rates to reduce the instantaneous emission of NOx at transition phase and full load part of the load transient. This paper focuses on different kind of such load transients experienced by a vehicle on road. The engine has to go through certain predefined load to no load and again to full load at the end. Likewise, it has been tested with similar test procedure and environment inside the test cell at a particular engine speed. The EGR valves and exhaust throttle movements were synchronized manually during the transition from no load to full load to avoid the regulation of valves by Engine Control Unit. The NOx and CO2 emissions are measured at exhaust and intake manifold respectively with high time-resolution measurement system. The temporal transport delays of HP and LP EGR are quantified with instantaneous CO2 measurement. Comparison of normal transients (without EGR at full load) with transients (using HP EGR and LP EGR) is carried out. A hybrid strategy with both Low and High pressure EGR have been proposed to reduce NOx emissions. At last the advantage of using LP EGR over HP EGR has been quantified during this load transient operation.

Abbreviations

HP EGR	= High Pressure Exhaust Gas Recirculation
LP EGR	= Low Pressure Exhaust Gas Recirculation
VGT	= Variable Geometry Turbine
WLTC	= World harmonize Light vehicle Test Cycle
PWM	= Pulse Width Modulation
CAC	= Charge Air Cooler
ECU	= Engine Control Unit
DPF	= Diesel Particulate Filter

1. Introduction

The recirculation of exhaust gas inside the combustion chamber has become a well-known technique to reduce the exhaust emissions. Different studies have been conducted to reduce

NOx emissions and improve fuel economy with the help of high pressure and low pressure exhaust gases at steady state [11]. Considering real-world engine operation, however, very little part of it occurs at steady-state condition but in dynamic condition [4]. Indeed, the transient engine operation contributes much more to the total amount of emissions over newly developed driving cycles than steady-state engine operation [5]. Moreover, these upcoming homologation cycles like WLTP and RDE are closer to real driving conditions than old NEDC cycles. Therefore, more focus has been given to improve the emissions during transient operation

In this paper, the effect of EGR on exhaust emissions during transient operations is observed. As per the previous work on heavy duty diesel engines, high pressure EGR loop configuration is prominent to control the transient emissions.[1] while, low pressure (LP) loop configuration has become a standard in automotive engines since it presents well-known advantages over the high pressure (HP) loop [12]. The main reasons are that the EGR and air mixing is better and also LP EGR can be further cooled using the charge air cooler.

2. Methodology

The type of transient operation performed at a constant engine speed in this study is called load transient. These kind of transients consists of a tip-in operation from absolutely no load to full load with insertion of small amounts of EGR rate (either HP or LP) at full load. According to the current engine calibration when engine runs on the operating point outside of EGR zone, there isn't any exhaust gas mixed with the intake air. Therefore, the effect of introducing EGR at full load (outside EGR zone) on the performance and emission of the engine has been studied.

The position of variable geometry turbine is important for the turbocharger response. The engine response is different with different positions of Variable Geometry turbine after pushing the pedal [3]. The parametric study is carried out with different VGT positions to find the fastest torque and boost pressure evolution, which can be used as reference for the further experiments. The manual PWM signal to close the VGT to 62%, 66%, 70%, 78% and 100% was sent through INCA while performing a transient (from pedal position of 13 to 100%). **Figure 1** shows the boost pressure with different closing of VGT. Where, closing of VGT up to 70% seems a best solution to provide fastest boost pressure evolution than closing the VGT fully.

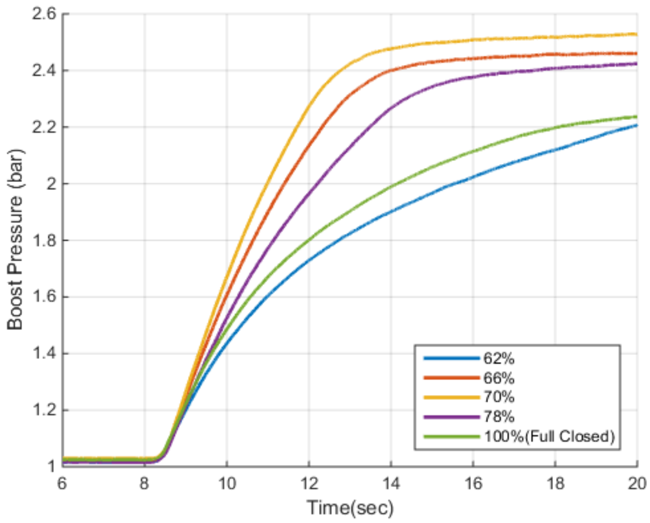

Figure 1: Boost Pressure (pressure at the intake manifold) with different percentage closing of variable geometry turbine at 1500 RPM

Looking at the transient operations in WLTC cycle, the density of these kind of transients is more at 1500, 1750, 2000 RPM engine speeds. Therefore, 1500 RPM is selected to perform this kind of transient. To perform transient operations (Load transients) and to have an idea about the EGR transportation, a special experiment is designed (considering the operating conditions faced by the vehicle during roundabout road). It consists of following steps,

1. The engine is running at 50% load to achieve the perfect heated state
2. Cut the fuel supply for 3-4 seconds, letting the engine rotate at the 1500 rpm(**Cranking**)
3. Push the pedal to 100% (**tip-in**)
4. When the torque is reached to steady state remove the pedal to 13% (**tip-out**)

During the tip-in operation, different configurations of EGR are used with 5% and 8% mass flow rate.

- Without EGR
- Low pressure EGR
- High pressure EGR
- Non-cooled high pressure EGR

In the first case, no EGR was introduced during tip-in operation, however, in the second and third case Low pressure and High Pressure EGR were introduced respectively with 8% and 5% mass flow rate. In the last case, a similar procedure is carried out using high pressure EGR, but without using the HP EGR intercooler. The coolant flow through the HP EGR intercooler is bypassed by an external duct with the appropriate valve arrangement.

3. Experimental Setup

3.1 Engine Specifications

The engine used in the experiments was a Renault R9M 1.6 liter Euro-5 specification diesel engine. The CAC was placed in a reservoir filled with coolant to control the temperature of air going inside the engine. The exhaust line was slightly modified with long length to install the probes for exhaust gas analyzer and opacimeter. Moreover, it consists of a diesel particulate filter and after treatment system right after the turbine from a conventional turbocharger on the production engine. The engine is controlled by a regular Engine Control Unit (ECU) with Euro-5 calibration. The ECU was connected to a computer with INCA software from where it was possible to modify and monitor the engine parameters through engine actuators and sensors. As the ECU calibration restricts to control the valves as per the requirement during transient operations, turbine nozzle geometry and EGR valves were controlled manually through INCA software. The high pressure EGR intercooler is bypassed by creating an external circuit for the coolant going inside the EGR intercooler to observe the effect of cooled and not cooled high pressure EGR on the NOx emission.

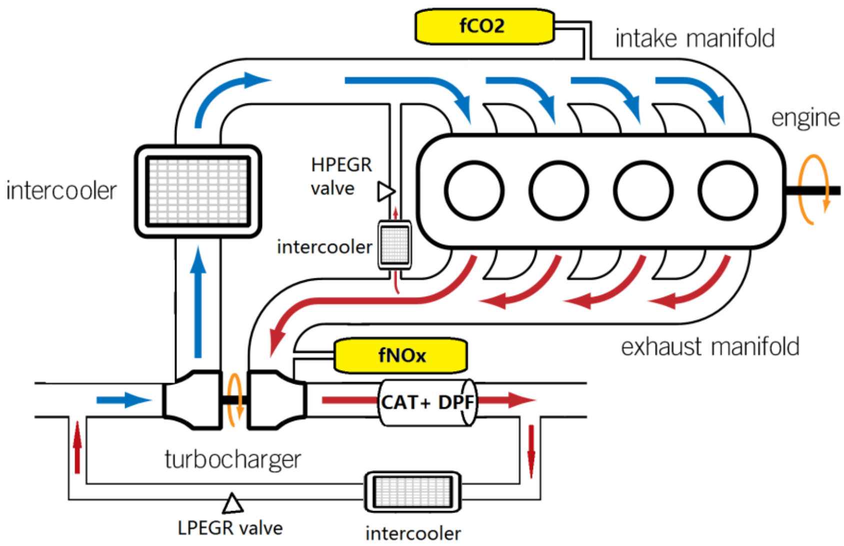

Figure 2: Layout of diesel engine with the experimental setup used in the experiments with Fast response emission measurement system.

3.2 Fast Emission Measurement System

As discussed above the important objective of this study is to measure the EGR rate and its effect on NOx formation inside the cylinder. For that purpose, a fast measurement system is needed to quantify EGR and NOx concentration during the transient operation [1]. Therefore, unlike conventional chemiluminescence detectors, a fast CLD500 system (also called as fNOx) from Cambustion© has been used to measure NOx concentration. The time response of this system is close to 2 milliseconds. Moreover, Non-Dispersive Infra-Red analyzer (NDIR500) from Cambustion© was used to measure the CO and CO2 concentration at the intake manifold. Presence of burned gas at the intake line can be observed with this device. The response time of NDIR500 is 8 milliseconds [13]. One probe (connected to CLD500) was installed upstream the turbine at the exhaust manifold (see **Figure 2**) while, the second probe (connected to NDIR500) was placed inside the intake manifold. The position of CO2 measurement probe was decided considering the dispersion of high pressure EGR inside the intake manifold.

3.3 Opacity measurement

The soot emission in the exhaust gas is measured by AVL439 opacimeter. This device's probe was installed downstream of the turbine. The opacity is measured in terms of percentage values with resolution of 0.01%.

3.4 EGR rate measurement

The EGR rate (fraction) inside intake manifold is calculated with CO2 concentration at the intake and exhaust of the engine. This CO2 concentration is measured by a gas analyzer from HORIBA systems© (see **Figure 2** for the location). The equation used for calculation of EGR rate is,

$$EGR\ rate = \frac{[\mathrm{CO2}]\mathrm{int} - [\mathrm{CO2}]\mathrm{air}}{[CO2]ext - [\mathrm{CO2}]\mathrm{air}}$$

Where, $[CO2]_{air}$ is the concentration of CO2 inside an air. The values obtained by this method are not instantaneous as the response time of conventional gas analyzer system is very low as compared to the combustion system. It also depends on the length of transportation duct carrying sampled gas to be analyzed gas analyzer. But this method can give an idea about the fraction of exhaust gases present in the intake air.

3.5 Acquisition system

The measurement of data with high frequencies by CLD500 and NDIR500 system needs to be acquiesced with higher acquisition frequency. Therefore, a data acquisition system from YOKOGAWA is used with an acquisition frequency of 1 kHz, which is for sure higher than 500Hz of CLD500 and 125Hz of NDIR500 system.

3.6 Control of actuators

The most critical thing during the transient operation is to control different valves simultaneously as per requirement along with the movement of the pedal. The current experimental facility provides, a separate actuation system to control pedal position while, EGR valves, VGT and Exhaust throttle can be controlled through INCA software connected to the ECU. Movement of valves requires a PWM signal sent through this INCA software. Therefore, corresponding PWM signal values for the respective valve position of HP and LP EGR have been already determined to get the required mass flow rate of EGR during full load steady state point (with VGT position to 70%). Exhaust throttle remains open during transition from no load to full load.

As the pedal actuation and EGR valves' movement are controlled by two different systems manually, we have a slight synchronization error (Human error). This error is discussed in the analysis section of this paper. The valve movement during tip-in operation is shown in the **Figure 3** and **Figure 4**.

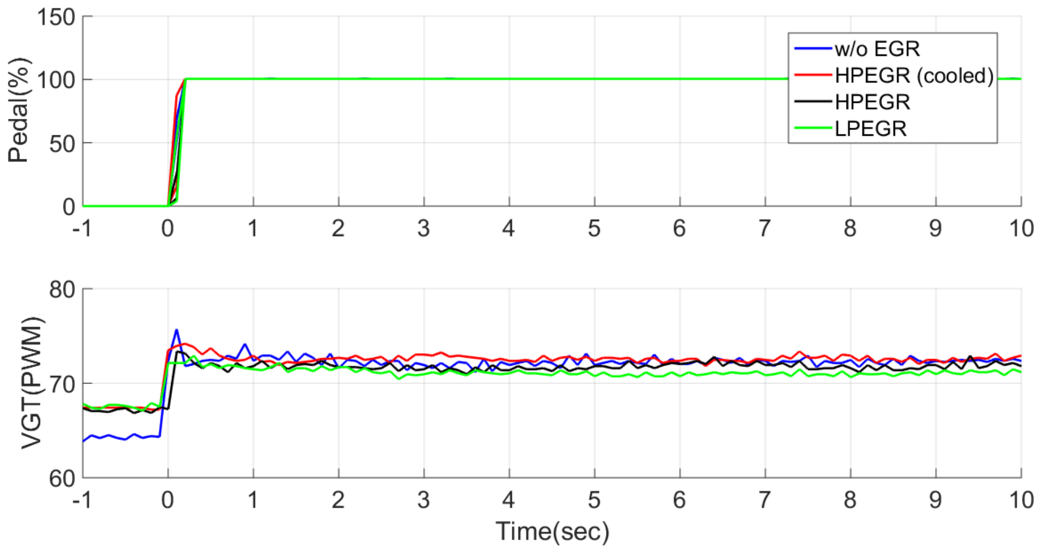

Figure 3: Synchronization of pedal actuation with optimized VGT positions controlled by a PWM signal through INCA software

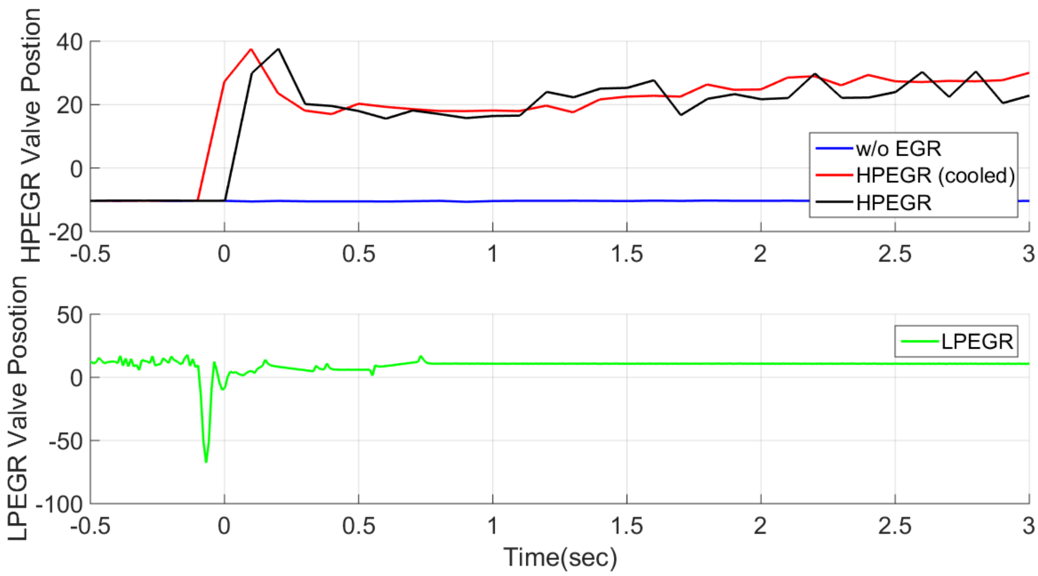

Figure 4: Synchronization of high pressure and low pressure EGR valve positions controlled by a PWM signal (volts) through INCA software

4. Results and discussion

4.1 EGR rate

To determine the reliability of Cambustion© system, each operating point was repeated with different EGR rates (5% and 8%) at high load. The focus has been given to the tip-in operation from the designed experiment to analyze the effects of the EGR introduction during load transient operation.

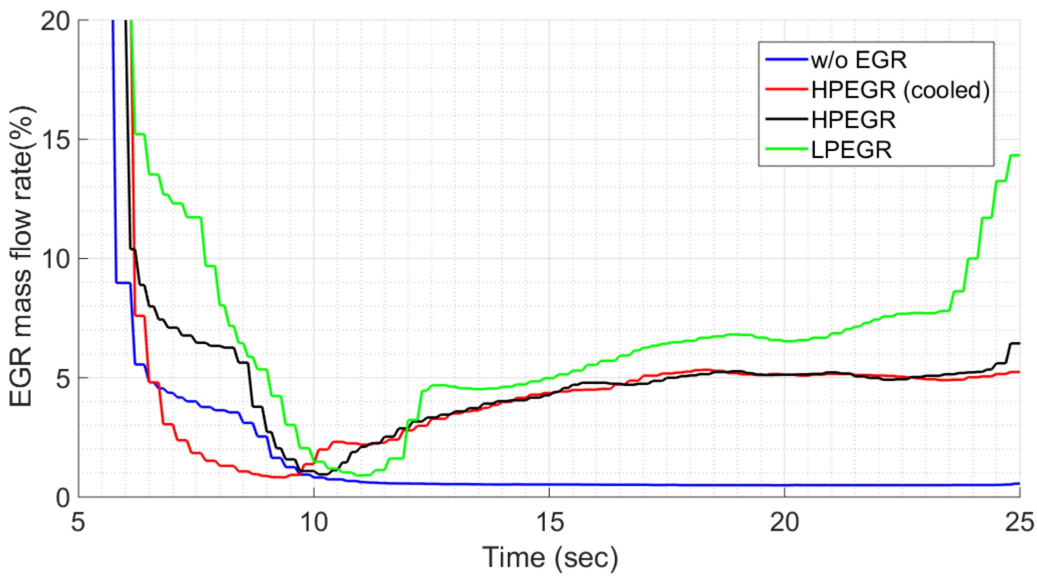

Figure 5: EGR rate (5%) measured by HORIBA systems during Tip In operation from absolutely no load to full load for different configurations of without EGR, LP EGR and HP EGR (cooled and not cooled).

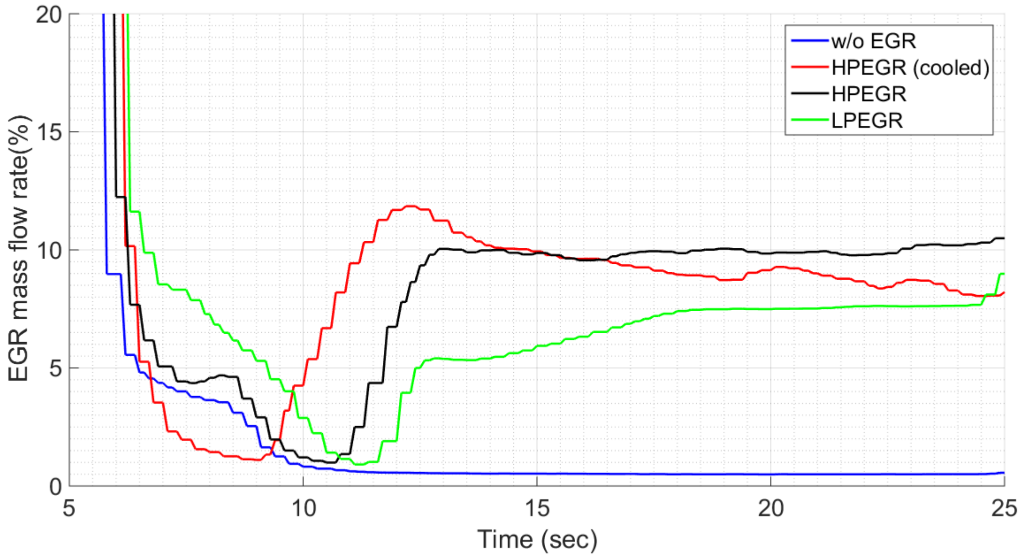

Figure 6: EGR rate (8%) measured by HORIBA systems during Tip In operation from absolutely no load to full load for different configurations of without EGR, LP EGR and HP EGR (cooled and not cooled).

As discussed above, The EGR rate was calculated by the equation 1 with CO2 concentrations with the slow response measurement system. Therefore, delay in the measurement of EGR rate is can be seen in the **Figure 5** and **Figure 6**. The values are high at beginning of transient because, during cranking phase (without any fuel injection), we only have air in the cylinder, which proves that measurement of CO2 concentration in the exhaust is close to atmospheric concentration. This causes the denominator close to 0, giving very high and unreliable values for EGR rate.

During tip-in operation, CO2 concentration in exhaust increases until it gets stabilized at certain value at full load. Likewise, the calculated EGR rate reaches to the anticipated value (5% and 8%) with the EGR valve positions measured beforehand at 1500 RPM. The evolution of low pressure EGR is little late than high pressure EGR. But the final steady state value is close to 5% in **Figure 5** and 8% in **Figure 6**.

To avoid confusion, a color scheme is followed for different configuration. The color codes are,

- Blue for data without any EGR at high load (normal transient)
- Red for HP EGR which is cooled with EGR cooler at the full load
- Black for HP EGR but not cooled
- Green for LP EGR at full load

4.2 NOx emissions

NOx emission at the exhaust manifold upstream of turbine are shown in **Figure 7**. A random peak is observed right after the pedal has been pushed, following a certain reduction in every configuration irrespective of the type of EGR introduced during transient operation. The same nature of the NOx emission curve has been observed with 8% EGR at full load (see **Figure 8**).

Due to good mixing of EGR with intake air, low pressure EGR configuration gives less NOx values at steady-state (around 50% less than the configuration without EGR). However, increase in percentage of EGR to 8% at full load, HP EGR configuration (both cooled and not cooled configurations) shows less NOx emission than LP EGR (this could be explained by high soot formation in **Figure 12**). The first peak appeared right after the change of pedal position seems random as no trend is observed in this sudden rise of NOx measurement with different EGR configurations. But, it is obvious that the steady-state NOx emission are reduced with the use of EGR. Moreover, it has been observed that, NOx concentration values with and without cooling of HP EGR configuration are nearly same. That means cooling of high pressure EGR does not have notable changes on NOx emission in the exhaust.

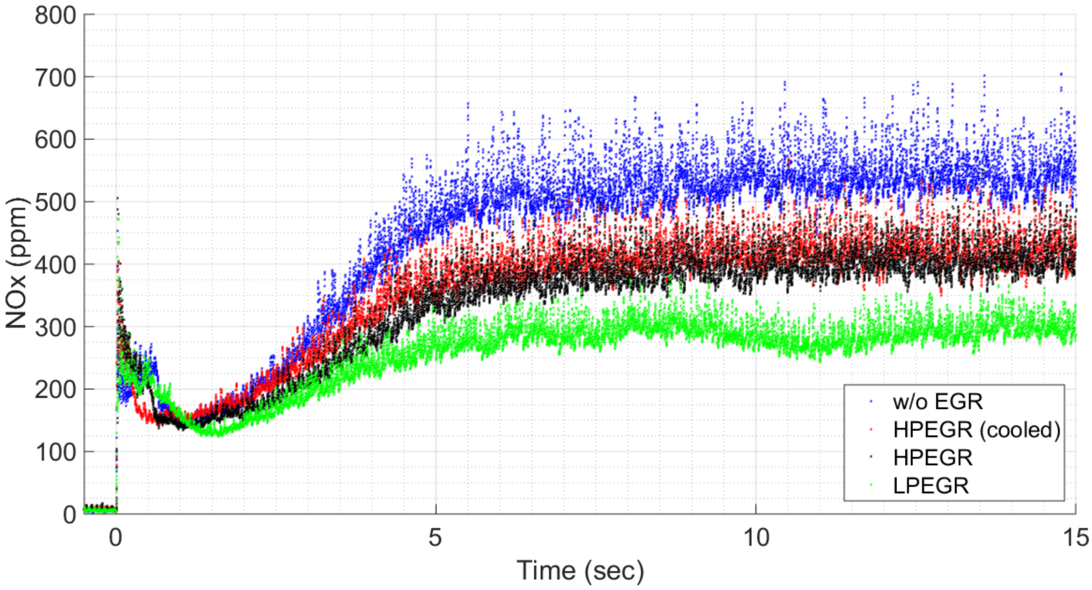

Figure 7: NOx concentration measured by CLD500 system at exhaust manifold during Tip In operation from no load to full load with different configurations, without EGR and 5% of LP EGR and HP EGR (cooled and not cooled)

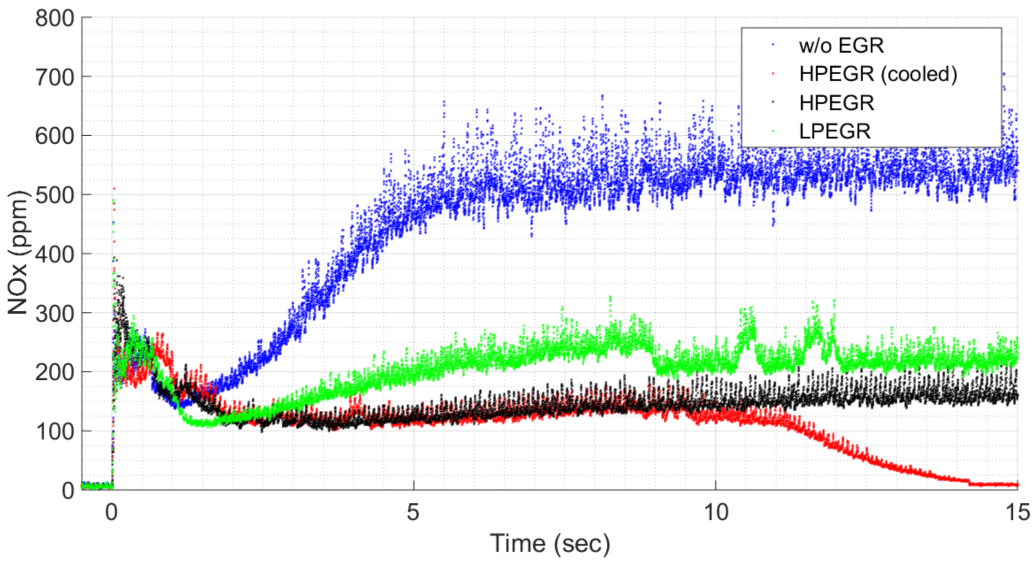

Figure 8: NOx concentration measured by CLD500 system at exhaust manifold during Tip In operation from no load to full load with different configurations, without EGR and 8% of LP EGR and HP EGR (cooled and not cooled)

4.3 CO2 Emissions

The CO2 concentration measurement shows highly dispersed values of CO2 concentration explaining dispersion of HP EGR inside the intake manifold (see **Figure 9** and **Figure 10**). The curve in blue states that there is no EGR except air, while low pressure EGR gives higher concentration than high pressure EGR with the same EGR rate. The transportation of EGR after tip in is explained in the analysis section.

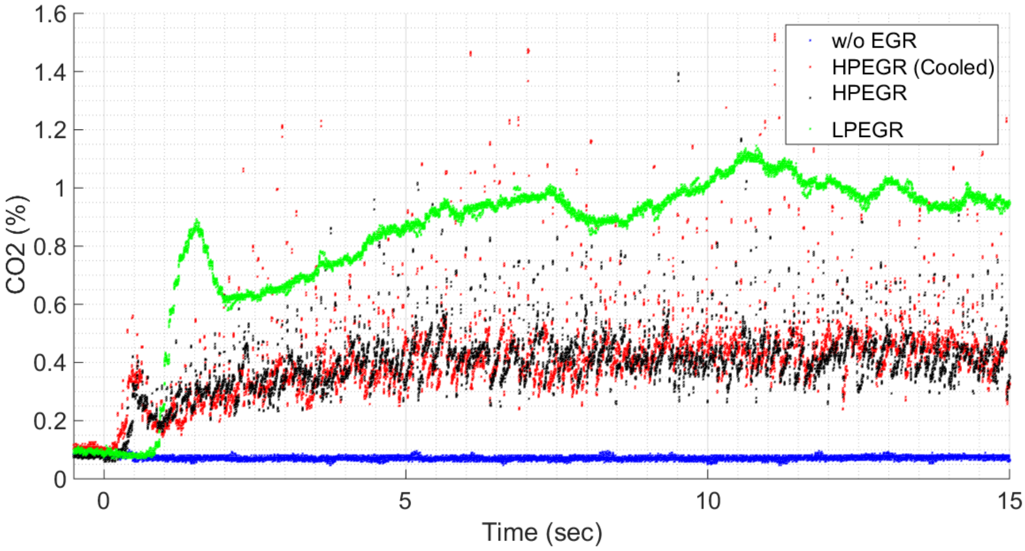

Figure 9: CO2 concentration measured by NDIR500 system at the intake manifold during Tip In operation from no load to full load with different configurations, without EGR and 5% of LP EGR and HP EGR (cooled and not cooled)

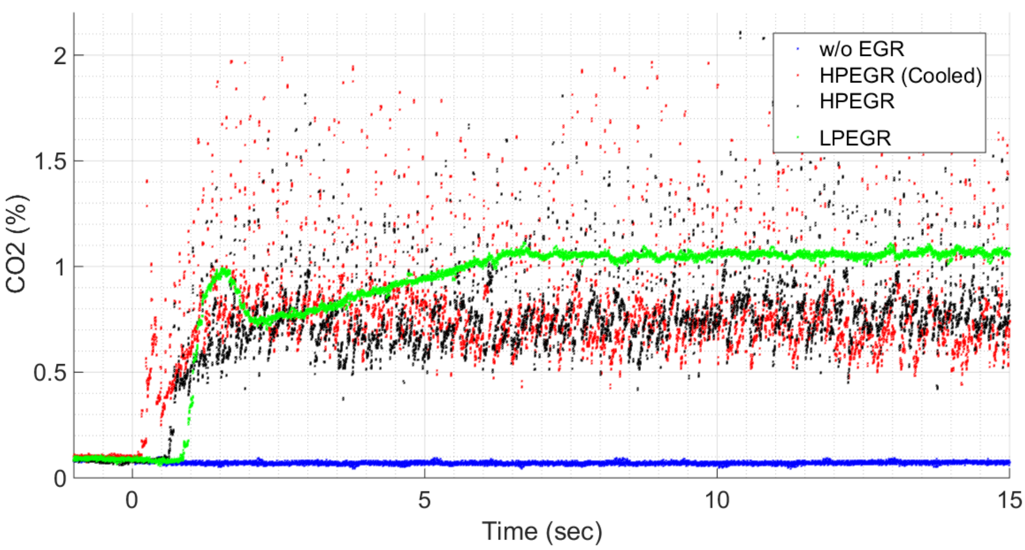

Figure 10: CO2 concentration measured by NDIR500 system at the intake manifold during Tip In operation from no load to full load with different configurations, without EGR and 8% of LP EGR and HP EGR (cooled and not cooled)

4.4 soot

Looking at the soot formation measured by opacimeter (AVL439) at 1500 RPM. A high opacity peak is observed at the beginning (see **Figure 11**). Sudden increment in injected fuel, while, transportation delay of the air mass flow (see **Figure 13**) engine suffers a deficiency of air which causes an increment of soot in the exhaust gas. From the measured values it seems, opacimeter gets saturated in first 2.5 seconds and the evolution is same for all the tests for all configurations. Therefore, no difference in peak values has been spotted for different EGR types. The steady state measurement is explainable with the measured NOx and rate of EGR,

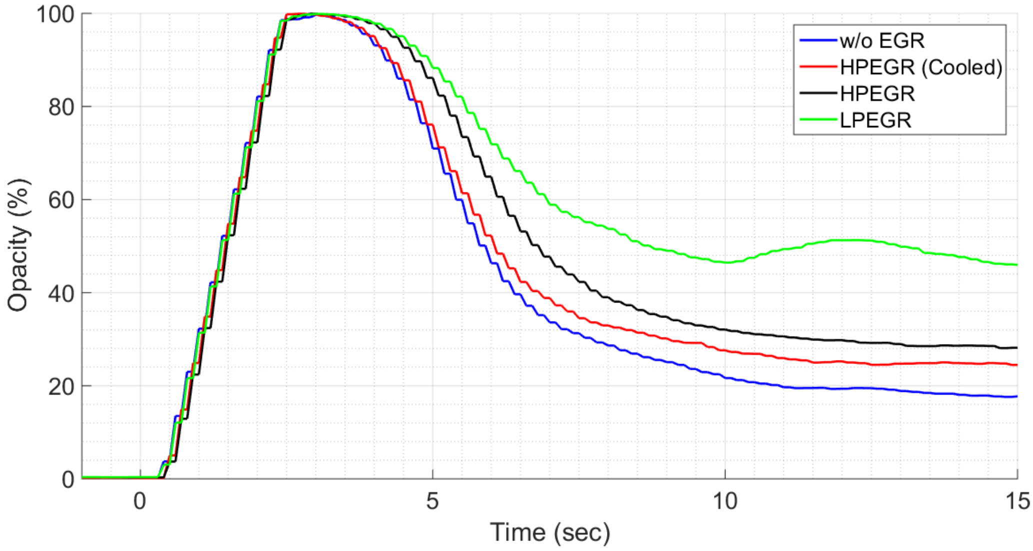

Figure 11: Opacity measured in percentage absorption during Tip In operation from no load to full load with different configuration of EGR (5%) at full load.

In the second case, the 8% EGR rate has caused more soot formation, which can be seen in **Figure 12**. All measured values except the blue curve without EGR, saturated the opacimeter. Hence, results with 5% of EGR at full load are considered for the further analysis because the opacity measurement for the tests with 8% of EGR at full load are not good enough. Moreover, this overproduced soot makes the combustion probe dirty causing it difficulties in measuring the NOx emission accurately just before the turbine.

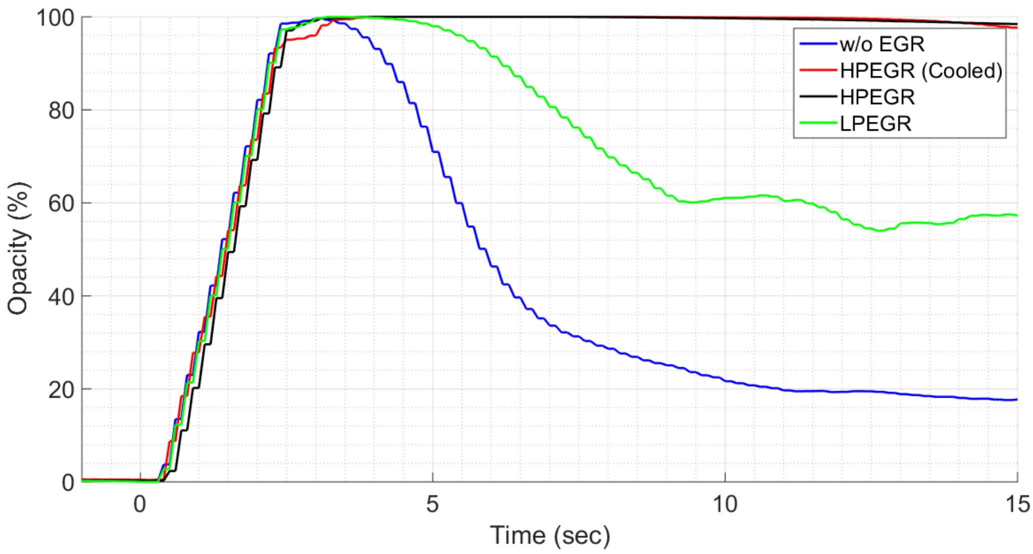

Figure 12: Opacity measurement in percentage absorption during Tip In operation from no load to full load with different configuration of EGR (8%) at full load.

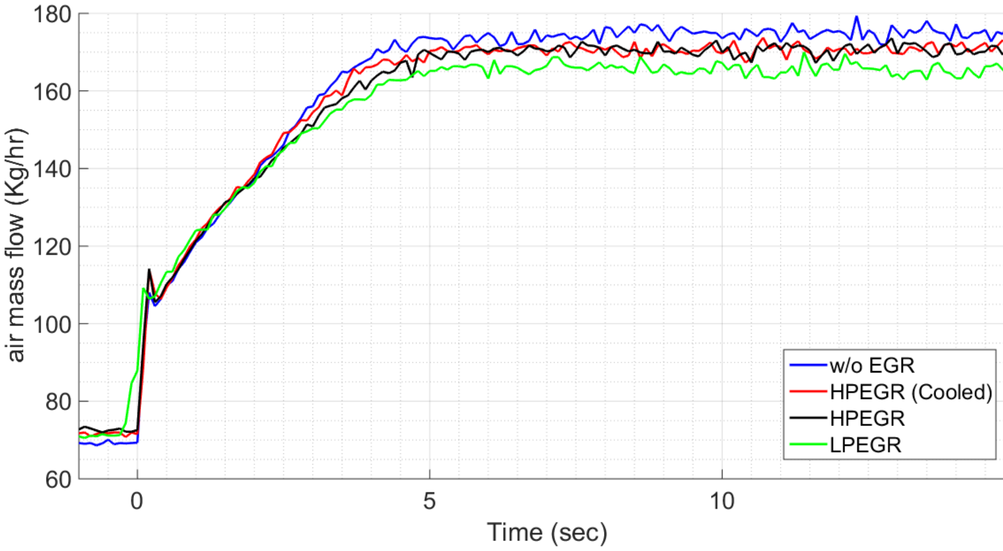

Figure 13: Air mass flow during the Tip In operation from no load to full load with different EGR (5%) configurations

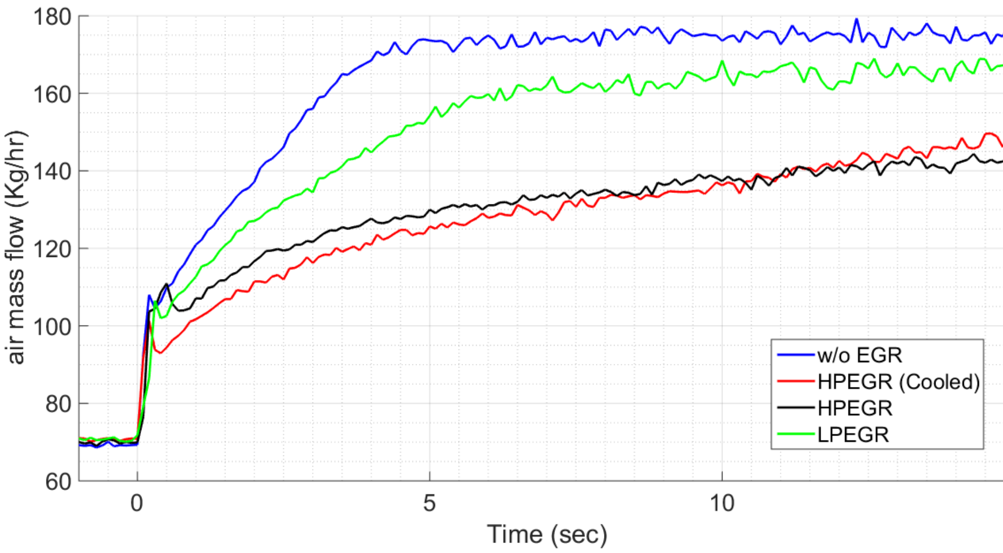

Figure 14: Air mass flow during the Tip In operation from no load to full load with different EGR (8%) configurations

4.5 EGR Temperature

Thermocouple installed after the HP EGR intercooler shows a difference in temperature measurement with and without intercooler (see **Figure 15**). The delay in temperature rise can be explained by the thermal inertia of a thermocouple. The high pressure EGR valve was closed during the cranking phase before tip-in operation. Therefore, we can see similar low temperatures at the beginning.

In case of high pressure EGR configuration, the temperature evolution using an intercooler (red curve) is found slower than the one without using an intercooler (black curve). That means, bypassing an intercooler is effective to recirculate high pressure EGR without cooling. The similar trend with elevated values of temperature is observed with 8% mass flow rate of EGR. (See **Figure 16**)

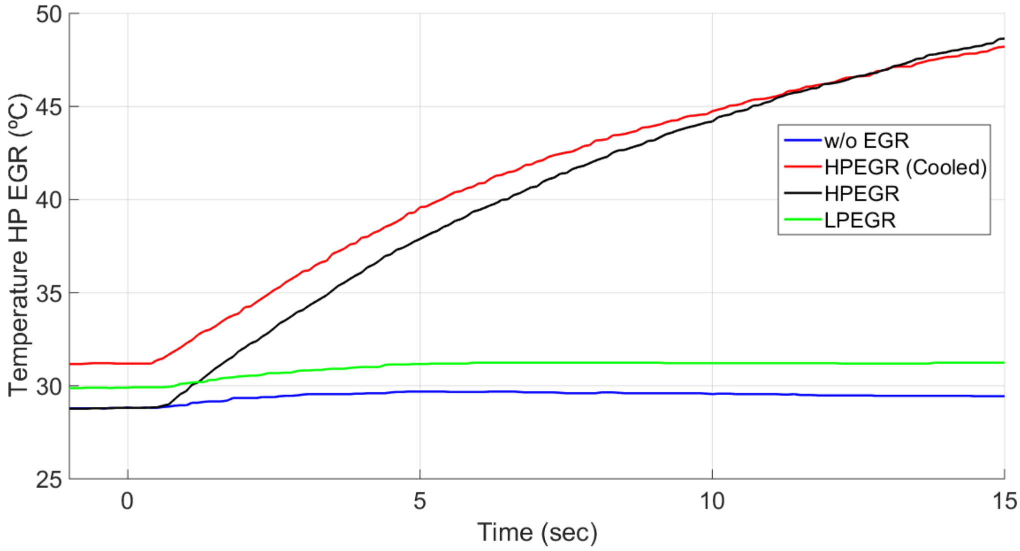

Figure 15: Temperature after HP EGR intercooler during the Tip In operation from no load to full load with different EGR configurations (5%).

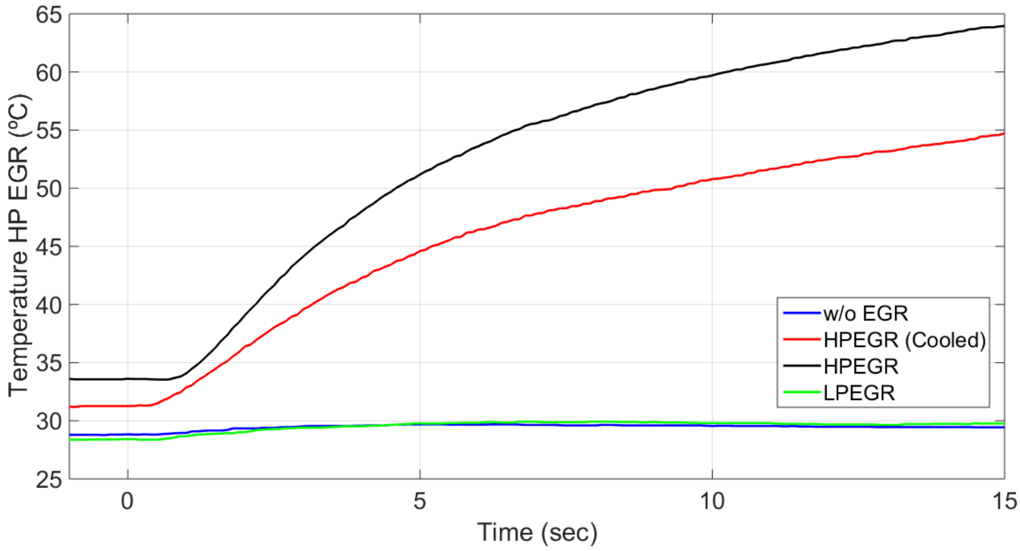

Figure 16: Temperature after HP EGR intercooler during the Tip In operation from no load to full load with different EGR configurations (8%).

4.6 Torque Response

Looking at the torque response, introduction of 5% EGR at full load is not causing much difference in the torque at steady-state (see **Figure 17**). In LP EGR configuration, fast response in torque, during first 2 seconds after tip-in explains delay in arrival of exhaust gases to the combustion chamber through intake line. Cooling of HP EGR hasn't shown any effect on torque evolution, whereas at steady state, not cooled HP EGR gives higher torque values than cooled HP EGR.

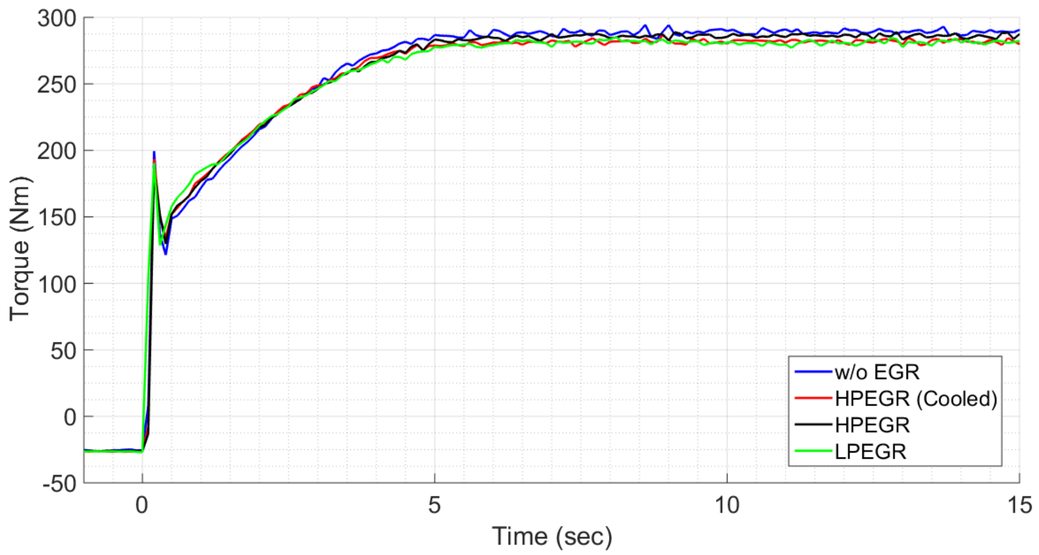

Figure 17: Torque provided by the engine during Tip In operation from no load to full load with different configurations, without EGR, 5% of LP EGR and HP EGR (cooled and not cooled).

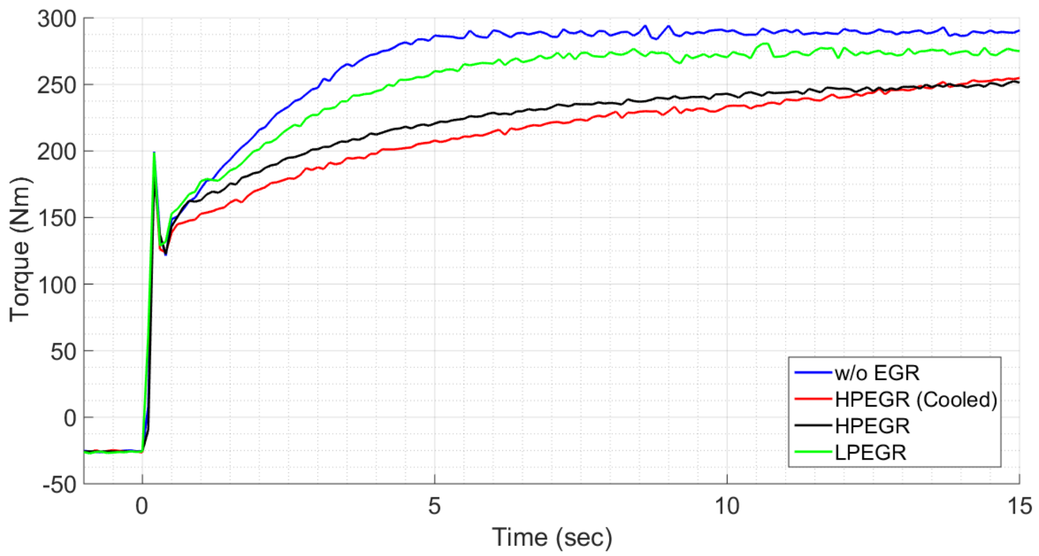

Figure 18: Torque provided by the engine during Tip In operation from no load to full load with different configurations, without EGR, 8% of LP EGR and HP EGR (cooled and not cooled).

In the case of 8% EGR at full load, due to lack of air mass flow (see Figure 14) in HP EGR configuration (cooled and not cooled) the torque response gets slowed (Figure 18).

4.7 Injected Fuel and air mass flow

As the injected fuel is controlled by the ECU, the smoke limitation strategy is activated which explains the reduction in injected fuel in the case of HP EGR (cooled and not-cooled) (see Figure 20). Air mass flow rate evolution (from Figure 14) is very slow for this configuration, reducing air to fuel ratio up to the minimum limit.

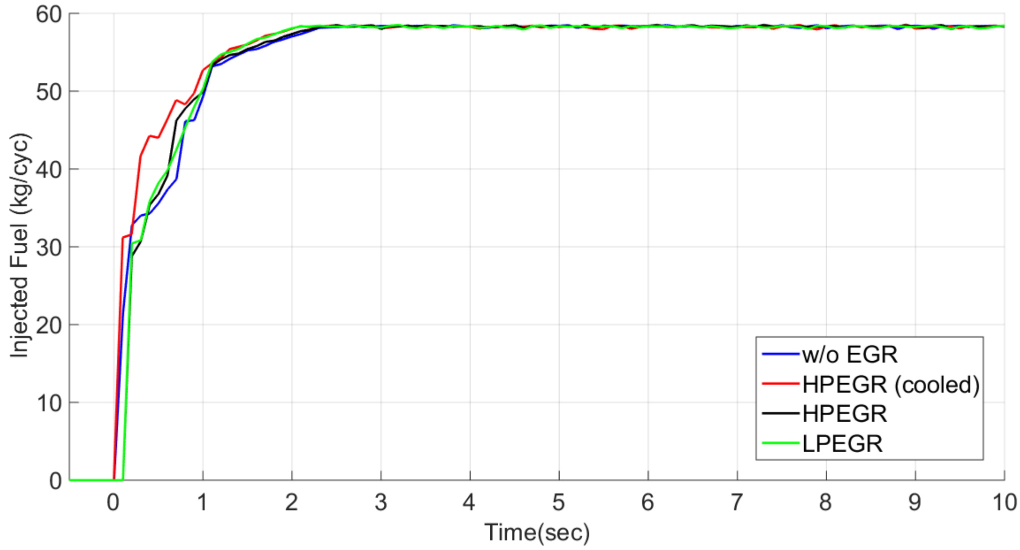

Figure 19 Mass of fuel injected per cycle during the Tip In operation from no load to full load with different EGR (5%) configurations

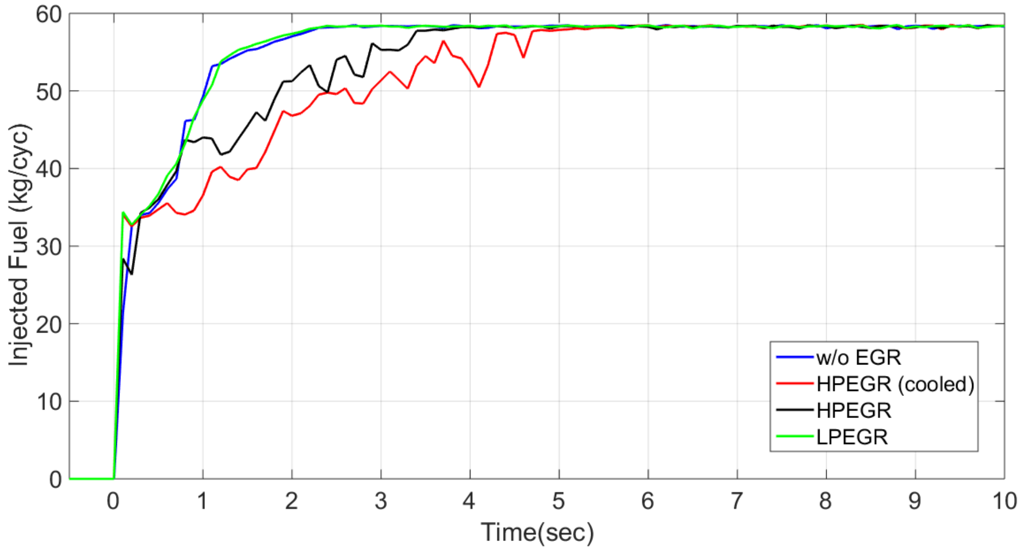

Figure 20: Mass of fuel injected per cycle during the Tip In operation from no load to full load with different EGR (8%) configurations

5. Analysis

5.1 CO2 and valve actuation

The movement of EGR valve is recorded (in volts) inside ECU. After plotting, this movement of EGR valves and instantaneous CO2 concentration at the intake manifold (see Figure 21), we can clearly observe the delay in transportation of EGR. As the valves were actuated manually, synchronizing with the pedal shift, there is certain shift in actuation time of HP EGR valves. They are not actuated at the same time (0 sec). The corresponding delay is transferred in the CO2 measurement on time scale. Therefore, it suggests that LP EGR requires around 1 second to arrive at intake manifold from the moment, when the LP EGR valve is actuated. While, HP EGR takes around 0.25 seconds to reach intake manifold. Please consider, the HP EGR line was modified to include an intercooler from the traditional production engine.

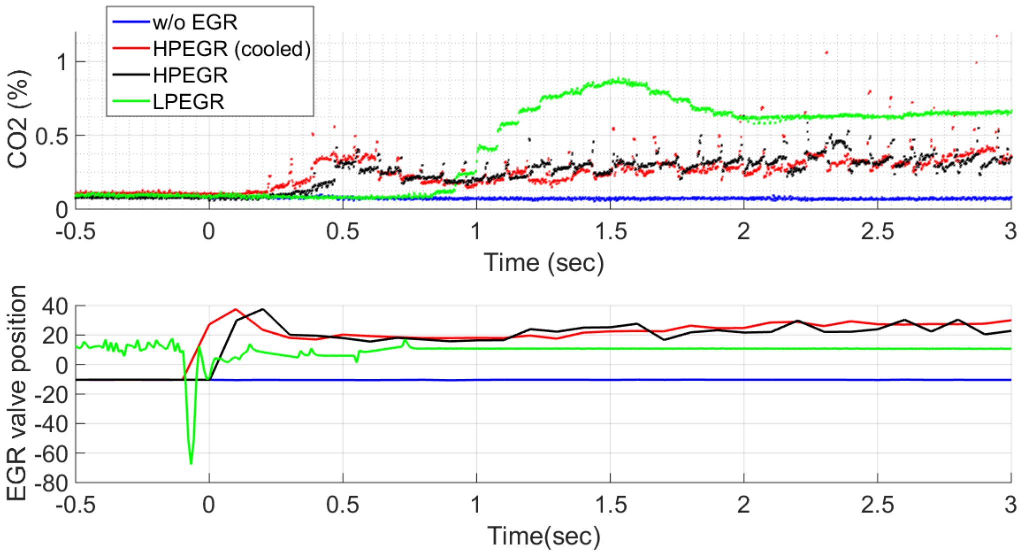

Figure 21: CO2 concentration measurement at the intake manifold with the position of LP EGR and HP EGR valve during the transient operation to provide 5% EGR at full load

5.2 NOx and CO2

After considering the transportation delay in in LP EGR and HP EGR, we can observe that the effect of these delays are translated to the NOx measurement with CLD500 system.
According to Figure 22, the first peak of NOx concentration is random phenomenon for first 0.25 seconds. Despite of repetition of experiments, no pattern has been observed for different EGR strategies. However, as soon as the EGR arrives to the intake manifold, the NOx concentration falls quickly. Therefore, HP EGR runs forward to curb the NOx formation as compared to LP EGR which takes around 1 second to arrive. This also explains that the NOx concentration is very sensitive to the HP EGR gas arrival in load transient.

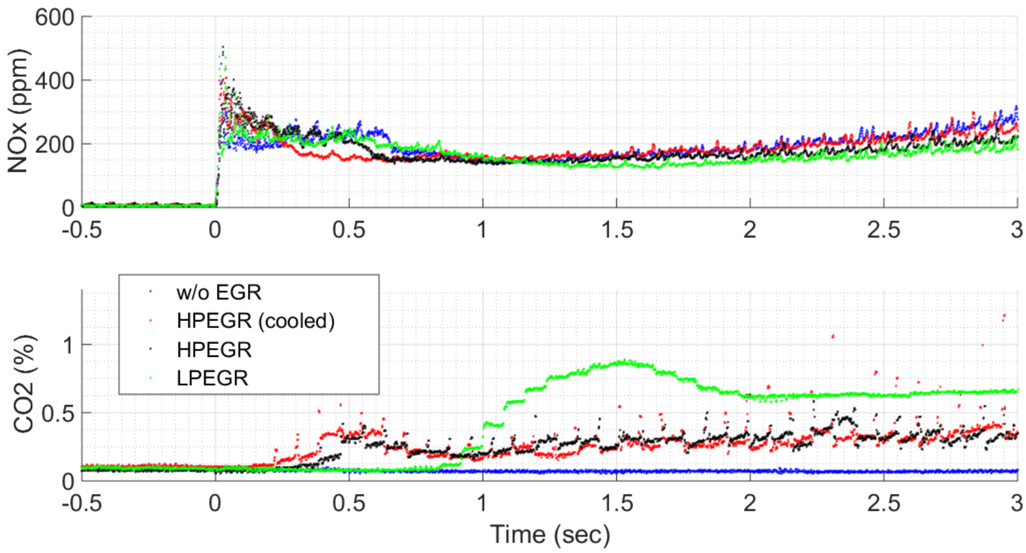

Figure 22: NOx concentration measurement at exhaust manifold with the concentration of CO2 measured at the intake manifold by the Cambustion© system for first 3 sec of transient operation to provide 5% EGR at full load.

5.3 NOx and Torque trade off

It is required to quantify the reduction amount of NOx emission with the use of different EGR configuration. This can be compared with the lost in performance by quantifying reduction in torque for the same

As stated above, the NOx peak doesn't have any trend with the use of different EGR strategies. Moreover, it lasts for only one fourth of a second. Let's neglect the first 0.25 seconds. Apart from this random peak, we have a delay in transportation of LP EGR of around one second after which NOx concentration is less than one in HP EGR case. Calculating the area under the curve can give the cumulative NOx emission in that one second. Hence, to quantify this profit of using HP EGR rather than LP EGR for the first 1-2 second, we have around 24% less NOx emission.

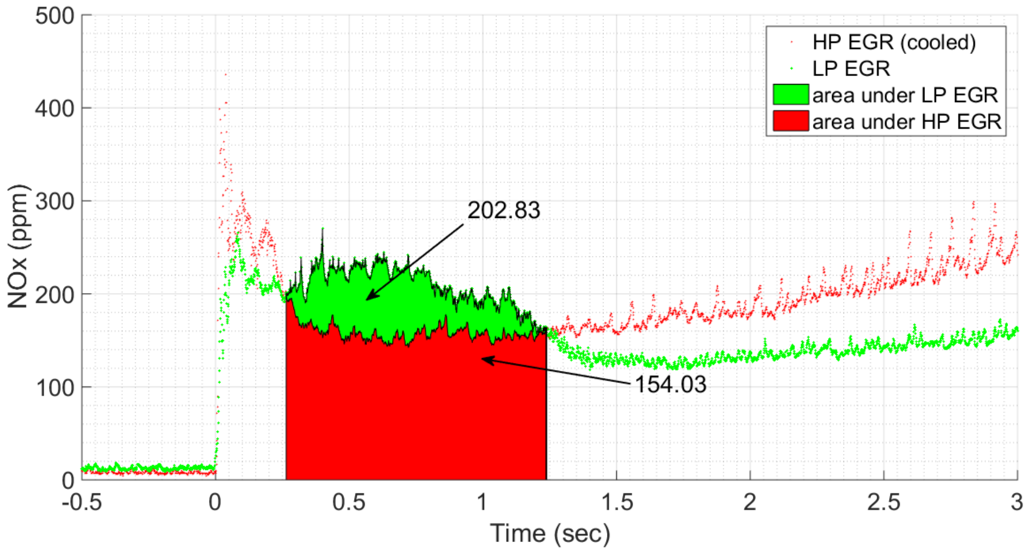

Figure 23: comparison of NOx emission between HP EGR (cooled) and LP EGR configuration during transient

Whereas, torque response of respective HP EGR cooled and LP EGR strategy (**Figure 24**) shows only 2% penalty in torque for the same amount of time.

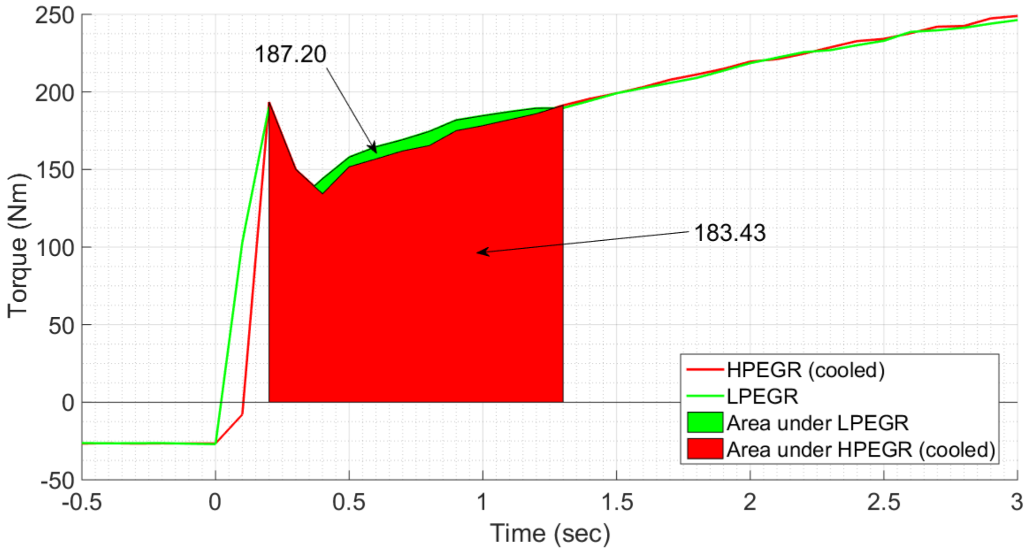

Figure 24: Comparison of torque response for HP EGR (cooled) and LP EGR configuration during transient operation

Hence, it is advantageous to use both high pressure and low pressure EGR to reduce the collective NOx emission during transient operation. HP EGR can be activated for just first 1-2 seconds till LP EGR arrives to the combustion chamber.

6. Conclusion

- This paper gives the insight of the use of a hybrid EGR system to reduce NOx formation during transient operation. A new strategy can be developed with HP EGR for first 1-2 seconds followed by LP EGR to reduce the NOx emissions during load transient operations.
- Introduction of 5% of exhaust gas at the full load (traditional known as outside of EGR zone) doesn't show remarkable reduction (around 2%) in torque of the engine compared to the NOx emission (reduced to around 24%).
- LP EGR during transient is better for faster torque response than HP EGR during load transients.
- With the advantage of fast Cambustion© system, it is possible to detect the small transportation delay in the arrival of EGR in the intake line during transient operation.
- NOx concentration during transient is very sensitive to the arrival of EGR in intake manifold. Sensitivity study can be carried out in future to measure the sensitivity of EGR at full load to reduce the NOx concentration in the exhaust.

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