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EGR TRANSIENT OPERATIONS IN HIGHLY DYNAMIC DRIVING CYCLES

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ABSTRACT−EGR is one of the proven and well tested strategies within the specific operating range of the engine. Necessity of an implementation of this exhaust gas recirculation all over the engine operating range is emerging. Therefore, a systematic study has been carried out to identify the specific and frequent transient operations on newly developed dynamic cycles like WLTC and RDE. To perform detailed observations, these transients are imitated individually on the diesel engine test bench. High frequency gas analyzers are used to track the instantaneous CO_2 and NOx concentration respectively at the intake and exhaust lines of the engine. A parametric study has been carried out using different valve movement profiles of the LPEGR and HPEGR during severe engine load change operations. An analysis is presented suggesting the best suited valve control during these harsh transients which can be helpful for transient calibration of a turbocharged diesel engine. The effect of length of Long route LPEGR line is also acknowledged. This study reveals the dynamic behavior of a diesel engine during transient operation with exhaust gas recirculation. It outlines the trade-off between performance and NOx emission and opacity for the initial phase of the transient before acquiring the steady state situation.

KEY WORDS : EGR Transients, Hybrid EGR, Diesel Engine, NOx emissions

NOMENCLATURE

LPEGR : low pressure exhaust gas recirculation
HPEGR : high pressure exhaust gas recirculation
EGR : exhaust gas recirculation
VGT : variable geometry turbocharger
BMEP : brake mean effective pressure
ECU : engine control unit
WCAC : water change air cooler
NEDC : new european driving cycle
WLTC : worlwide harmonized light vehicle test cycle
RDE : real driving emissions
PEMS : portable emission measurement system
CLD500 : Chemiluminescence Detectors
NDIR500 : non-dispersive infra-red analyzer
BSFC : brake specific fuel consumption
FL : Full Load

1. INTRODUCTION

It's been many years that exhaust gas recirculation strategy has been used to lower the temperature of combustion and to reduce NOx formation on high speed turbocharged diesel engines. Plenty of literature is available regarding effective implementation of both HPEGR (also known as short route) and LPEGR (also known as long route) (Maiboom *et al*., 2008; Khalef *et al*., 2016; Zamboni *et al*., 2017). Use of HPEGR decreases brake specific fuel consumption (BSFC) of an engine reducing pumping losses, while the homogeneous mixture of LPEGR with air reduces even more cylinder out NOx concentration comparatively at steady state (Zamboni and Capobianco, 2012). LPEGR increases the mass flow rate through the compressor shifting the operating point to a higher efficiency zone along with effective use of variable geometry turbo (Park and Bae, 2014). Looking at different benefits and drawbacks of these two systems, a hybrid system using both EGR configurations is also studied switching in-between at particular operating conditions on driving cycles (Luján *et al*., 2015). Specific split in flow between these two architectures has been optimized experimentally and with simulations in steady operations (Park *et al*., 2015; Park and Choi, 2016). However, increasing challenges of emission regulations with dynamic engine behavior, this system needs an update to match with real world driving conditions. Various technologies to curb the emissions during transient operation have been developed but, eventually they add the extra cost and weight to the engines (Brookshire and Arnold, 2007; Lana *et al*., 2016). On the other hand, the available EGR lines on production engines can be used conveniently to adapt with the new regulations cost effectively rather than inventing new technology.

In recent years, new concepts regarding driving cycles

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are becoming popular. Unlike NEDC their driving behavior is close to real driving conditions with dynamic nature. The WLTC is a World-wide harmonized Light duty Test Cycle which was developed under the working party on pollution and energy (GRPE) by many countries playing a crucial part in automotive industry. The main objective was to design the harmonized driving cycle from unified 'real world' driving database collected from different regions around the world (Tutuianu *et al*., 2015). It is acknowledged as well representative of on road real driving conditions. Portable emission measurement systems (PEMS) have made available measurements of on-road real driving emissions. Therefore the scope of type approval tests is not limited up to the test bench anymore. The traditional driving cycles and emission regulation procedures seem to be replaced by new advanced cycles like WLTP and RDE. As a consequence of the diesel gate scandal a lot of data on real driving emissions of Euro 6 cars has become available and published (Yang *et al*., 2015; Thunis *et al*., 2017). It has been mentioned that EURO 6 calibrated vehicles have the emissions more than the new regulation limits and need high conformity factor to pass the newly developed type approval process (Luján *et al*., 2018b; Triantafyllopoulos *et al*., 2018). In parallel, dynamic cycles like WLTC are being developed to represent the real driving conditions (Donateo and Giovinazzi, 2017). Retrospectively, the emissions strategies designed for steady state conditions are very much needed to be modified to cope up with the emissions. Various studies have been carried out to see the effect of emissions during new dynamic cycles based on cold intake conditions (Luján *et al*., 2018a), heated after-treatment system (Daya *et al*., 2017). The transient operations who are responsible for NOx emission (Yamada *et al*., 2011; Giakoumis *et al*., 2012) are studied specifically with fast emission measurement systems (Leach *et al*., 2019).

Regarding transient EGR, research has been done on small transient operations up to medium load with LPEGR (Reifarth and Angstrom, 2009, 2010) and mild transients with slow change in load on extra urban part of NEDC cycle (Black *et al*., 2007). Hybrid EGR technology has been also simulated to see the effect on the transient air performance and emissions (Heuwetter *et al*., 2011). Presence of EGR delays the duration of transient operation. HPEGR is quiet fast compared to the LPEGR due to the short length of EGR line. While, LPEGR valve movement with exhaust throttle are quiet sensitive for the overshoot in burned gas mass fraction transport (Luján *et al*., 2018c). Some strategies regarding the control of EGR during this transient event has been tested and published. One of the strategies consists of implementation of 'threshold limit' for burned gas mass fraction, to reduce the NOx peaks during mild transients and air fuel ratio, to reduce the particle matter formation. However, this strategy is not useful when the transient events last up to full load, where the air-to-fuel ratio (AFR) is already close to 1. Moreover the strategy of burned gas mass fraction will reduce the performance of the engine too much (Darlington *et al*., 2006). Apart from diesel engines, there are some methods that has been developed on gasoline engines, regarding estimation of LPEGR rate considering transportation delays from the EGR valve to intake valve of the cylinder which can be helpful to design the LPEGR control during transients (Liu *et al*., 2016). This study acts as a continuation of above studies in order to find out strategies for emission reduction with existing production engine structure without increasing cost related to high-tech after treatment system or whole other new technology.

This paper focuses on highly dynamic cycles and engine behavior during transient operations on those driving cycles. First part of the paper consists of cycle analysis of WLTC and RDE. The data obtained by running a 2l engine with different cycles is analyzed to identify typical transient operations. Additionally, an algorithm developed by TNO, Netherlands with the help of Markov chains (Balau *et al*., 2015; Kooijman *et al*., 2015) was used to create 90 different driving cycles which are analyzed similarly.

In the scond part, the selected transient operations are repeated on a diesel engine test bench to analyze the gas path behavior and cylinder out emissions. The emissions are measured with high response NOx and CO_2 measurement system to examine dynamics. Aditionally, a parametric study is performed with different valve movements during a selected transient operations. This study reveals the effect of EGR valve movements on performance and emissions. Finally, a tradeoff between those emissions and performance for transients is presented. Apart from this, a typical transient operation at a roundabout is performed specially to find any discrepancy from the selected trasients.

2. CYCLE ANALYSIS

This section includes, analysis and selection of transient operations with high pedal shifts also called as harsh Tip-In and Tip-Out operations. This analysis is carried out on class 3 WLTC and some real driving cycles to identify the typical frequent transient operations.

A vehicle model was created for a sedan class vehicle with 2 litre turbocharged diesel engine (description is given in the "Experimental Setup" section) considering the forces on the vehicle driven with a velocity profile of different driving cycles. The main characteristics of vehicle model regarding aerodynamic coefficients and powertrain ratios are given in Table 1. Various parameters like engine speed, torque, gear ratios were recorded along with emissions and actuator movements like EGR valves and VGT.

2.1. WLTC

Figure 1 shows a test run of typical class 3 WLTC cycle with urban and extra urban part. The blue fill represents the

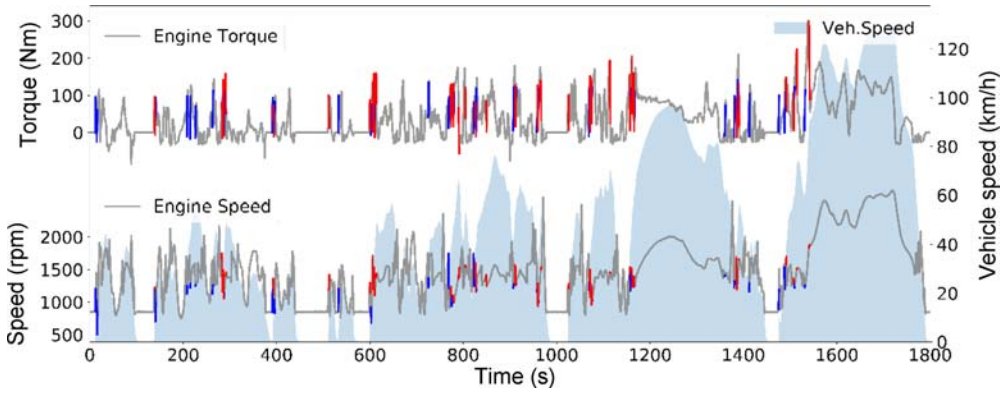

Figure 1. WLTC Cycle profile with torque and speed of turbocharged 2 lit. diesel engine and representation of harsh transient Tip-In (blue) and Tip-Out (red) operations with absolute torque change of more than 80 Nm. The time interval for this change in torque is 1 s. Vehicle speed is plotted in lightblue on the right y-axis.

Table 1. Vehicle specifications used for the vehicle model with given diesel engine.

Parameter	Value
Vehicle Mass (kg)	1430
C_x	0.3
ρ (kg/m^3)	1.2

vehicle speed in kilometers per hour while the gray curves show the engine torque and speed across the cycle. The portions marked in red and blue lines on each variable plot are actually the changes in discreet values of the respective variables in 1 second with exceptional torque change greater than 80 Nm (blue) or less than − 80 Nm (red). This type of situation can happen whenever the driver pushes or releases the pedal, or changes the gear ratio while driving. As one can imagine, with a change in absolute torque more than 80 Nm (which is equal to change in BMEP of around 5 bar) is surely a harsh change of state for a steady running engine. An interesting fact that is observed is that the engine speed does not respond with the similar amount of variation as the engine torque. The red lines represent Tip-In operation while blue lines are for Tip-Out operations. Closed look at the data reveals that the length of absolute torque change line in top plot is higher as compared to the length of absolute change line in engine speed. The engine speed almost remain constant during the load change. These type of transients are also called as “Load transients” where there is a change in load at particular speed of an engine.

To identify the engine speed ranges where these transient operations are frequent, all the operating points of the WLTC cycle undergoing change in absolute torque more than 80 Nm are plotted on the engine map, as depicted in Figure 2. The color scheme of the points represents a change in engine torque between the current and the successive operating point on the cycle. The are arrows pointing towards the direction of change in torque (or BMEP) of the engine. These engine maneuvers represent harsh transients. The vertical nature of arrows confirms the behavior of these transients as load transients. The arrows

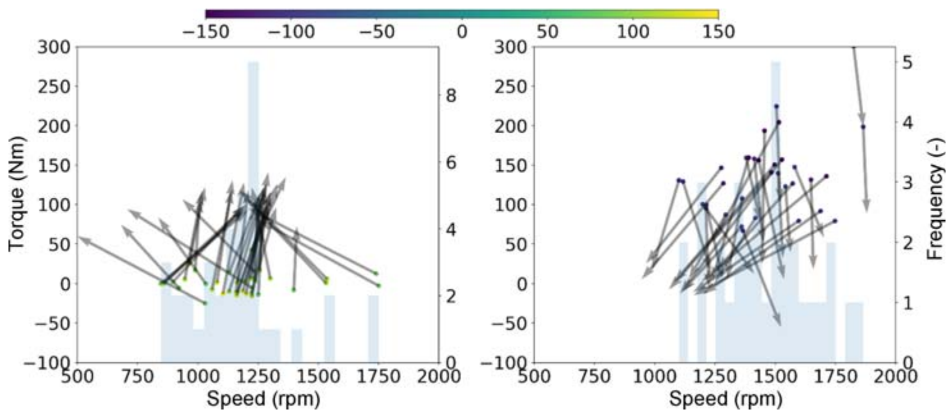

Figure 2. Harsh transient operation Tip-In (left) and Tip-Out (right) in WLTC cycle with torque change more than 80 Nm (arrows) along with their histogram (frequency) in light blue.

pointing towards the upper left corner show the gear change to higher ratios while the ones pointing to higher engine speed and low load (towards lower right corner) represent the downward gear shift. Although most of the transients are spread over the range from 800 to 1750 RPM, the frequency of typical harsh Tip-In kind of transients on WLTC cycles is higher close to 1250 RPM while the harsh Tip-Out operations are spread over the higher engine RPMs. The trail of consecutive arrows represents the continues operation of change in torque with higher torque change within the consecutive seconds.

2.2. RDE

As stated earlier, Real Driving Emissions are measured directly on vehicle with PEMS. No standard cycle is followed for the measurement of RDE nonetheless some constraints designed by (European Parliament & Council of the European Union, 2016). Therefore, in this study, two approaches were used to analyze the real driving conditions. First, actual vehicle-speed demand was measured with a vehicle on different routes across conventional roads passing the constraints of real driving dynamics framed by European Union. This new cycle was programmed with a vehicle model on the engine test bench to measure brake torque and emissions. Secondly, a computer algorithm with the help of Markov chain, developed by TNO (Netherlands) was used to create 90 real driving cycles (Gong *et al*., 2010; Balau *et al*., 2015). The vehicle model which was used to analyze WLTC cycle in previous section, came handy for the similar analysis with these real driving cycles.

The engine torque and engine speed measured on above RDE cycle are plotted in Figure 3. The harsh transients represented by the red and blue lines have absolute values more than 80 Nm, as the time between current and successive operating points is 1 second. The higher amount of harsh load transients presented in this case are also evident from the graph. Looking at the engine map for this driving conditions in Figure 4, we can say that the high frequency range for Tip-in and Tip-Out operations is from 1000 to 2000 RPM. The inclined arrows represent the transient from gear change while vertical arrows give idea of load transient on the engine map.

The additional cycles generated by the new algorithm are also analyzed similarly. A 2-D histogram in Figure 5 shows the frequency of 90 real driving cycles on the engine

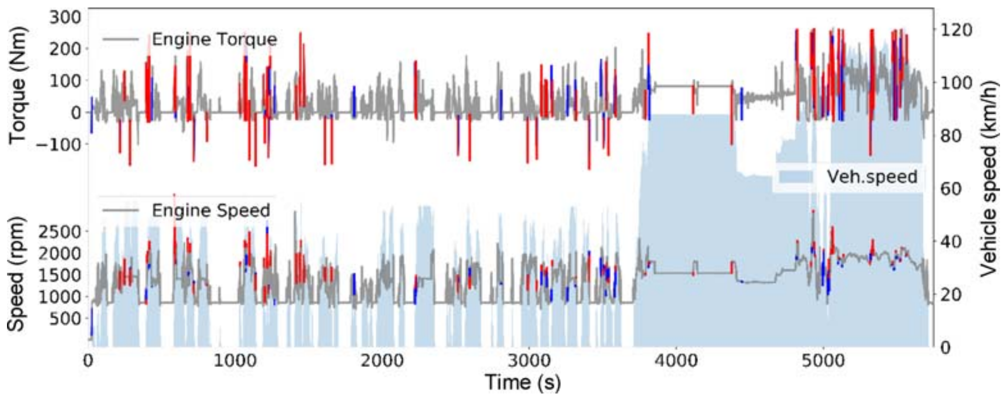

Figure 3. Real driving cycle profile with torque and speed of turbocharged 2 l diesel engine and representation of harsh transient Tip-In (blue) and Tip-Out (red) operations with absolute torque change of more than 80 Nm. The time interval for this change in torque is 1 s. Vehicle speed is plotted in lightblue on the right y-axis.

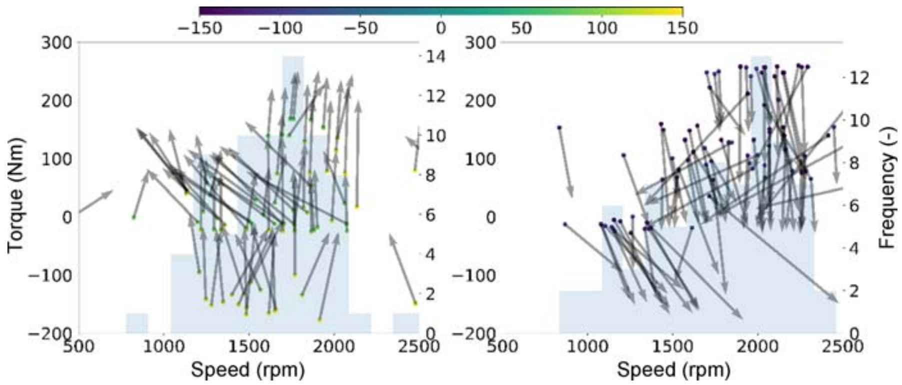

Figure 4. Harsh transient operation Tip-In (left) and Tip-Out (right) during real driving cycle with torque change more than 80 Nm (arrows) along with their histogram (frequency) in light blue.

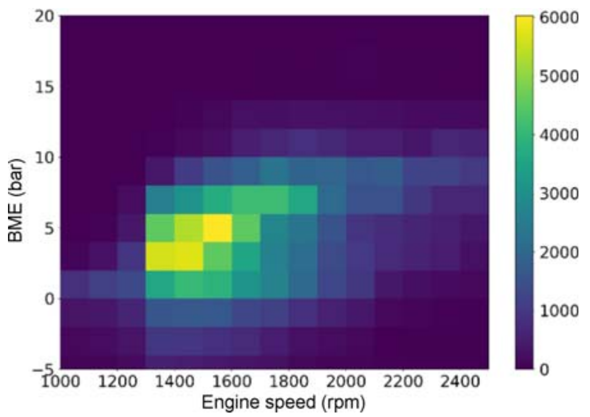

Figure 5. 2-D histogram of engine operating points from the randomly generated 90 real driving cycles from TNO algorithm.

map with bin size of 100 RPM and 2bar BMEP. Most of the operating points lie between 1200 to 2000 RPM. For every cycle, the change in BMEP with respect to change in engine speed is calculated for every dt of 1 seconds as in the analysis of WLTC cycle. It has been seen that, The number of load transient operations with the same gear are 1000 times higher than the ones which come through changein gear.

3. EXPERIMENTAL SETUP

3.1. Engine

The engine used in the experiments is a 4 cylinder 2 litre displacement direct injection turbocharged diesel engine with integrated water CAC in the intake manifold and fitted with compact HPEGR and LPEGR lines. The HPEGR line is integrated in the intake manifold and has a rail injecting the exhaust gas directly upstream the intake valves. A separate heat exchanger was used with PI control to maintain a target intake air temperature through the WCAC. The engine is mounted on engine dynamometer with braking strategy to maintain constant engine speed. The measured data from engine sensors is recorded by an acquisition system. Moreover, the same software is used to control the actuators such as the exhaust throttle, HPEGR and LPEGR valves. Apart from engine sensors, additional devices such as a hot-wire anemometer is used to measure the air mass flow to the engine after the air filter along with various pressure sensors and thermocouples attached to the air path. The fuel consumption is also measured with an external fuel balance measurement in addition to the estimation of the injected fuel performed by the ECU.

3.2. Emission Measurement

3.2.1. NOx

The raw NOx emissions during transient operation are measured by two separate emission measurement systems

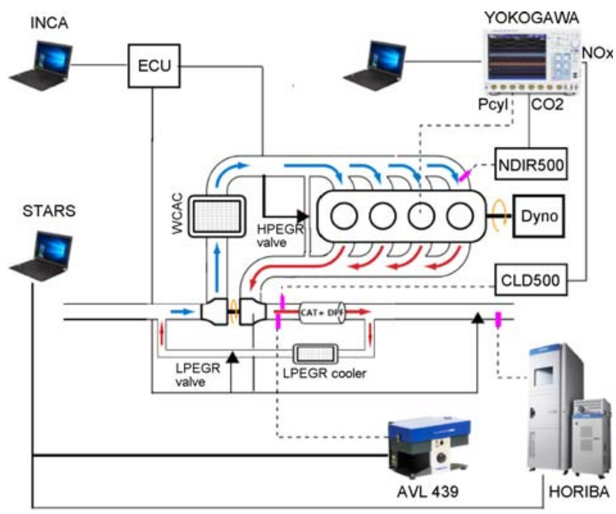

Figure 6. Schematic diagram of the engine test bench.

with the sensors located downstream of the turbine. The first one is a conventional slow response gas analyzer (which is appropriate for steady state measurement) while another one is the fast response systems (Buchwald *et al*., 2006). The fast analyzers consist of chemiluminescence detectors, a fast CLD500 system (also called as fNOx) to measure NOx concentration downstream of turbine. The time response of this system is close to 2 milliseconds (Leach *et al*., 2018). Figure 7 confirms the temporal response during a typical load transient operation from low load to full load, measured with the two gas analyzers.

Evidently Horiba measurements are slow compared to the other. They are also delayed due to length of insulated pipe from the engine to the sensor device but it is corrected in the figure. Due to diffusion process during transportation of sample to the gas analyzer and dilution, the slow measurement fails to detect the rapid dynamics and the peaks of NOx. On the other hand, the CLD500 is fast enough to measure the instantaneous pollutant concentration in the exhaust line during transients. To

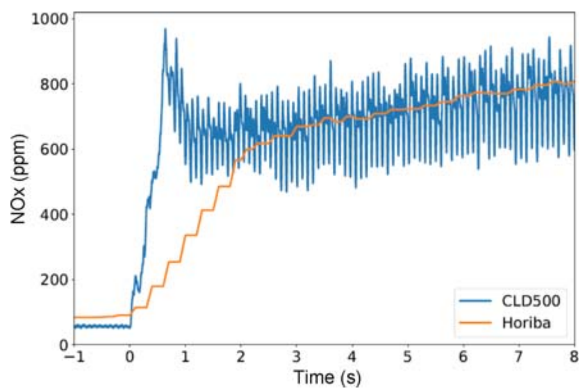

Figure 7. Time response of NOx measurement during a typical transient operation by Cambustion (CLD500) and Horiba systems.

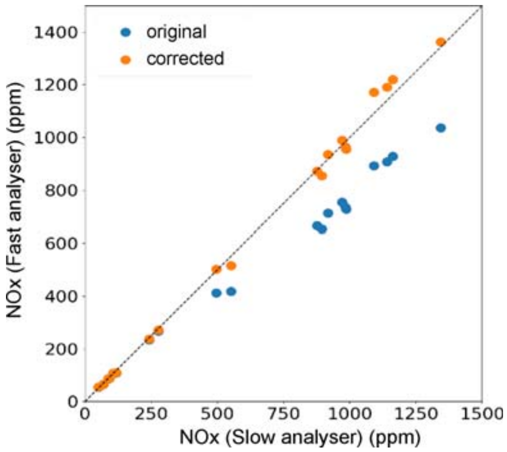

Figure 8. Steady state fast and slow gas analyzer measurements and corrected values for fast gas analyzer.

calibrate the fast measurement system all over the NOx measurements done for steady operation, certain steady state steps in the pedal from low load to full load were performed. The NOx concentration downstream of turbine is measured with both systems. Figure 8 shows the correlation in the measurements of these fast and slow response gas analysers. The steady state measurements by CLD500 up to 400 ppm match with the measurements of other but as the NOx concentration increases further, CLD500 is found to be underestimating the real value, perhaps due to the sensor measurement is affected by the pressure at the point where sensor in installed on the engine (Blanco-Rodriguez, 2014). This under measurements are corrected by a multiplication factor depending on the measured NOx values by the same rapid response system.

3.2.2. CO_2

Non-Dispersive Infra-Red analyzer (NDIR500) from Cambustion was used to measure the CO_2 and CO_2 concentration at the intake manifold. Presence of burned gas at the intake line can be observed with this device. To have an exact idea of exhaust gas arrival at cylinder, the sensor was placed just before the intake valve after HPEGR port. The response time of NDIR500 is 8 milliseconds (Luján *et al*., 2018c).

3.2.3. Opacity

The soot emission in the exhaust gas is measured by an AVL439 opacimeter downstream the turbine. A pressure reducing device is installed between the sensor and the AVL439 as the measurement is carried at the high pressure points in the exhaust line. As the opacity is actually the unit of amount of light passed through the smoked screen, the values can be converted into FSN by using an empirical correlation (Lakshminarayanan and Aswin, 2017; Luján *et al*., 2018a). The measurements were carried out in terms of percentage values with resolution of 0.01 %.

3.3. Air Mass Flow Measurement

The air mass flow measurement at the intake manifold is very important to study and simulate the transient performance and emissions (Benajes *et al*., 2000; Benajes *et al*., 2002). The signal registered by the hot-wire anemometer is slow and measured far from the combustion chamber after air filter. It has to be corrected due to the effect of pressure waves travelling and the effect of air mass storage inside the intake system (Serrano *et al*., 2009) . Considering the compressible behavior of air, it causes a time delay in air mass flow measuring device and the actual air mass entering through intake valve. The new corrected air mass flow can be corrected by the Equation (1) which can be obtained by considering the ideal gas equation (pV = mRT) and conservation of mass.

$$m_{\text{out}} = m_{\text{in}} + \frac{dm}{dt}$$

$$\frac{dm}{dt} = \frac{V}{R} \times \frac{\Delta\left(\frac{P}{T}\right)}{\Delta(t)}$$

Where V is the volume between the hot wire anemometer and the intake manifold of the engine. m_{out} is the air mass flow at the intake valve while m_{in} is the mass flow measurement at the anemometer. Figure 9 shows the difference between measured and corrected air mass flow during a transient operation from low load to full load.

3.4. Exhaust Gas Recirculation

During transient operation, measurement of EGR rate going inside the cylinder is difficult as compared to steady state due to intricate design of intake manifolds, air path length and delays in gas arrivals during transient operation. Many experimental or model based methods have been used to estimate EGR mass flow rate during the transient operations. Some of these approaches are listed below:

(1) Characterizing EGR valve positions with air mass flow

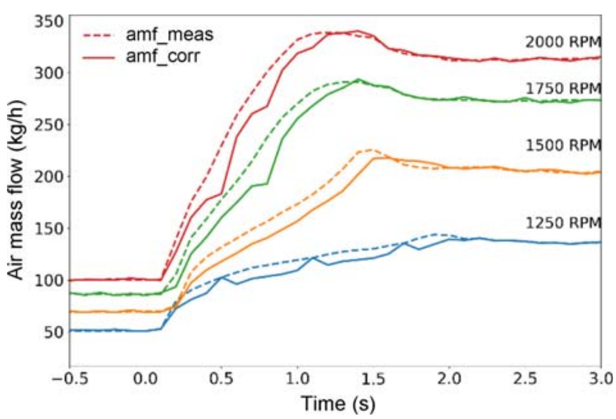

Figure 9. Measured and corrected air mass flow at the intake manifold during a typical transient operation from low load to full load.

at steady state, assuming the engine volumetric efficiency to be the same as the operation without EGR (Liu and Pfeiffer, 2015).

(2) Using two Cambustion NDIR500 sensors at the intake and exhaust to estimate the instantaneous EGR rate going inside the cylinder (Sutela *et al*., 2000).

(3) "Volume filling" effect using ideal gas law and conservation of mass used to estimate the transient EGR (Liu *et al*., 2016).

(4) Model based EGR rate observer design (Shutty, 2009).

(5) Intake oxygen sensor for EGR measurement (Soltis *et al*., 2016).

(6) In-cylinder pressure measurement (Chung *et al*., 2018).

For the given engine, due to the complexity of the intake manifold design and compactness, it was difficult to measure the EGR rate during the actual transient operations. So conventional Horiba system is used to measure the steady state EGR to determine valve positions at particular operating points and those positions were used during transient testing. The EGR rate (fraction) inside intake manifold is calculated with CO_2 concentration at the intake and exhaust of the engine. This CO_2 concentration is measured by a gas analyzer from Horiba systems (see Figure 6 for the location). The equation used for calculation of EGR rate is,

$$\text{EGR rate} = \frac{[CO_{2(int)}]-[CO_{2(amb)}]}{[CO_{2(exh)}]-[CO_{2(amb)}]}$$

Where subscripts *amb*, *int* and *exh* are related to ambient, intake and exhaust locations for the CO_2 concentration respectively. 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 Cambustion system. It also depends on the length of transportation duct carrying sampled gas to the gas analyzer. But this method can give the EGR valve positions to maintain as per quasi-steady operation during full load part of a transient.

3.5. Control of Actuators

The second and most critical issue during transient tests on test bench 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, other actuators like VGT, HP/LPEGR valves and exhaust throttle are controlled through INCA software. The corresponding PWM signals to control valve positions of HP and LP EGR have been already determined to get the required mass flow rate of EGR in full load steady state point. This is explained in the section of studies. As the pedal actuation and EGR valves' movements are controlled by two different systems manually, a slight temporal mismatch got induced in actuators movements during Tip-In and Tip-Out operations.

3.6. Acquisition System

High acquisition frequency system is necessary for the measurement of data recorded by CLD500 and NDIR500 system. Therefore, a data acquisition system from YOKOGAWA is used with an acquisition frequency of 10 kHz, which is for sure higher than 500 Hz of CLD500 and 125 Hz of NDIR500 system. The other variables like pressure and temperature were recorded with 10 Hz frequency.

4. METHODOLOGY

The identified load transient operations from the cycle analysis section are performed on the engine test bench with various EGR strategies at full load. Firstly, the determination of EGR valve positions is done on the 4 engine speeds at full laod. In the next step load transient operations are performed (with predecided valve positions) in the following section.

4.1. Full Load Steady State

Addition of EGR at full load creates a complex scenario considering the smoke limiter strategy, as the diesel engine already runs with lambda close to 1. This condition is critical for the formation of soot. Moreover, from the control point of view, it will hinder with the close loop control of boost pressure at full load. So, firstly, the EGR valves are controlled manually to find out the position to provide around 5 % EGR rate at full load in steady state. Secondly, these valve positions of HP and LP EGR valves are fixed for respective type of strategies, whenever engine operates on full load. Table 2 represent the 4 operating points where the EGR valve positions are determined.

In the case of HPEGR, as said before, due to complexity of the intake manifold, it was difficult to measure the EGR rate. With 5 % of LPEGR conditions at full load, the engine always exceeds the AFR limitations for soot formation. Therefore, the air-fuel ratio value is not a good parameter to determine the same operating condition for comparison of HP and LP configuration. However, HPEGR valve positions giving the same torque values as in LPEGR is can be used to see the effect on the emissions with similar performance. The effect of intake manifold temperature variations can be neglected here since the EGR rates are

Table 2. Full load steady state points with 5 % of EGR from LP and HPEGR system at iso-torque operation.

Speed (RPM)	EGR rate (%)	LPEGR (% open)	HPEGR (% open)	Torque (Nm)
1250	5 %	20.84	16.36	268
1500	5.1 %	20.84	26.78	342
1750	5.08 %	20.84	50.59	390
2000	5.1 %	20.84	44.64	393

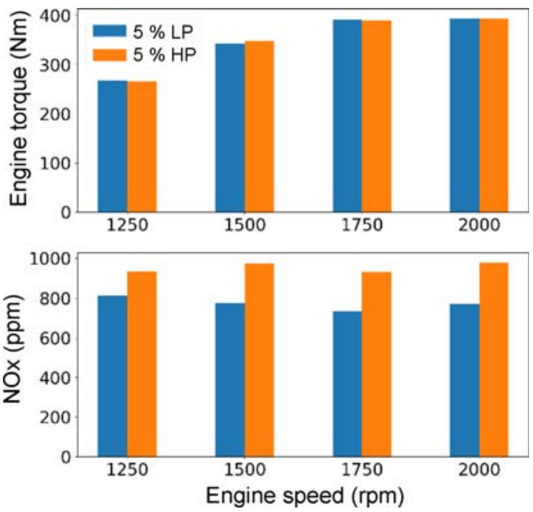

Figure 10. Iso-torque engine operation to have same composition of the HPEGR and LPEGR at full load for different engine speeds.

reduced and the air-EGR mixture temperature will not be significantly affected between LP or HP-EGR. Therefore, the HPEGR valve position was found out to deploy 5 % of EGR rate giving same torque values as in LPEGR as shown in Figure 10.

4.2. Transient Operation

Finally, the harsh transients were performed on 4 engine speeds covering the high density zones of transients on the engine map of different driving cycles. The selected engine speeds are 1250, 1500, 1750, 2000 RPM. All the Tip-In and Tip-Out operations were performed after the engine is warmed with coolant temperature above 80 ºC. To assess the worst case behavior during a particular case of Tip-In and Tip-Out operation, the pedal shift was carried out from 2 bar BMEP with around 40 % of LPEGR as per the ECU calibration to full load in a time less than a second. At the low load point, LPEGR valve was completely open and the exhaust throttle was used to control the air mass flow to the cylinder inside EGR zone.

After remaining for 15 seconds at full load, the pedal was shifted back to original position with 2 bar BMEP. Intake throttle was kept open all the time (as exhaust throttle is best suited to drive LPEGR than intake throttle (Reifarth and Angstrom, 2009)). The emissions and engine parameters (as explained in the experimental setup) were recorded for these 40 s. Different EGR configurations analyzed during these load transients are described in the Table 3.

5. RESULTS

5.1. Transient without EGR

A typical transient with the original calibration and different engine parameters for 1500 RPM is shown in Figure 11. When pedal is shifted to 100 %, to operating point outside of EGR zone, LPEGR valve closes completely while CO_2 concentration just before the intake valve reduces slowly to zero as there are exhaust gases present already in the intake circuit. Due to the compact design of LPEGR line, the transportation delay of the burned gases has been reduced considerably as discussed in (Luján *et al.*, 2018c). NOx emissions increase in particular way as soon as the pedal position is changed from low to full load. The observed evolution consisted a three step process where NOx increases up to a certain value until the CO_2 concentration starts to decrease at the intake valve. Thereafter, CO_2 starts decreasing and NOx evolves to a next step with higher value where fuel is getting limited as the AFR value goes below the smoke limiting value (the

Table 3. Transient operation studies with different EGR strategies.

Engine Speed (RPM)	Transient load progression	EGR at FL
Load transient without EGR at FL		
1250, 1500, 1750, 2000 RPM	2bar-FL-2bar	0 %
Load transient with EGR at FL		
1250, 1500, 1750, 2000 RPM	2bar-FL-2bar	5 % LP
1250, 1500, 1750, 2000 RPM	2bar-FL-2bar	5 % HP
Load transient with LP profiles		
1250, 1500, 1750, 2000 RPM	2bar-FL	Prof5
1250, 1500, 1750, 2000 RPM	2bar-FL	Prof10
1250, 1500, 1750, 2000 RPM	2bar-FL	Prof15
Load transient at roundabout		
1500 RPM	2bar-0bar-FL-2bar	5 % LP

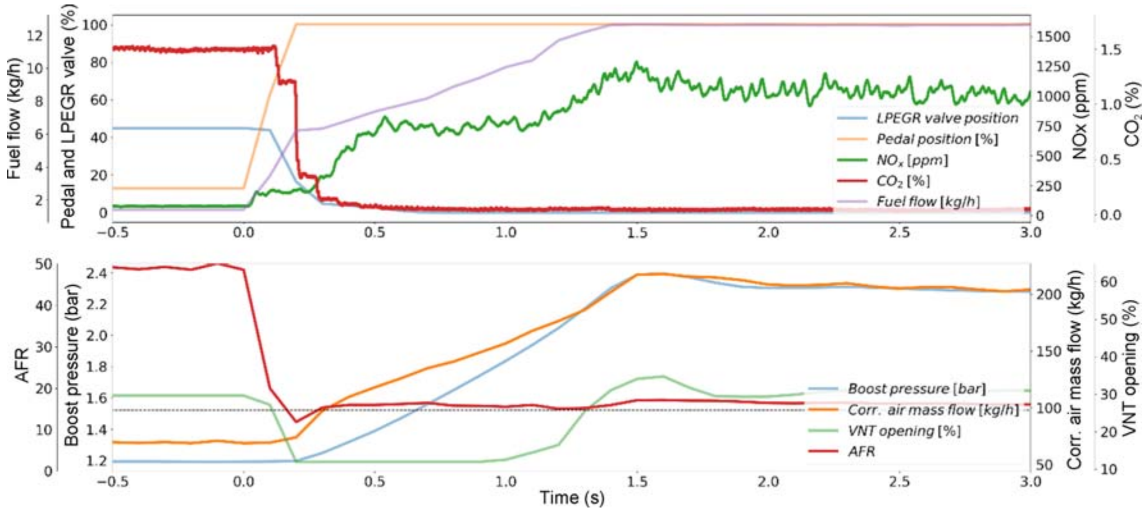

Figure 11. Measurements of different engine parameters and emission along with valve actuations during a typical Tip-In operation from low load to full load at 1500 RPM

black dashed line represents stoichiometric AFR). This part could be coined as a “waiting zone” where fuel is being limited. The fuel starts increasing further as soon as air arrives with the delayed turbo boost and it eventually increases in-cylinder temperature and eventually NOx formation to even a higher final value as a last step.

On the other hand, during the Tip-Out operation from the full load to 2 bar BMEP running conditions (see Figure 12), fuel reduces back instantly while the air goes down sluggishly creating high AFR more than 150. Moreover, as the operating point goes back into the EGR strategy zone opening again LPEGR valve, CO_2 concentration in the intake line evolves with a time delay leading to a peak of NOx for that short period of time as seen in the Figure 12. Later, due to combination of LPEGR valve and closing of exhaust throttle, a high flow of LPEGR is recirculated which leads to an important reduction of NOx (Luján *et al.*, 2018c). As the EGR rate demand is high, the LPEGR valve opens completely and the flow control of EGR and air flow is transferred to exhaust throttle, which partially closes to increase the pressure in the exhaust line so as to increase the EGR flow at the same time. The change in CO_2 near 1.5 seconds is due to this movement of exhaust throttle which can be seen in lower plot of Figure 12.

It is important to observe the turbocharger behavior during a transient operation. In the case of Tip-In operation, whenever pedal is pushed at the start of the operation, the variable geometry turbine closes the vanes reducing the cross sectional area to a value (12 % in this case) close to minimum to fulfil the boost pressure demand quickly. As

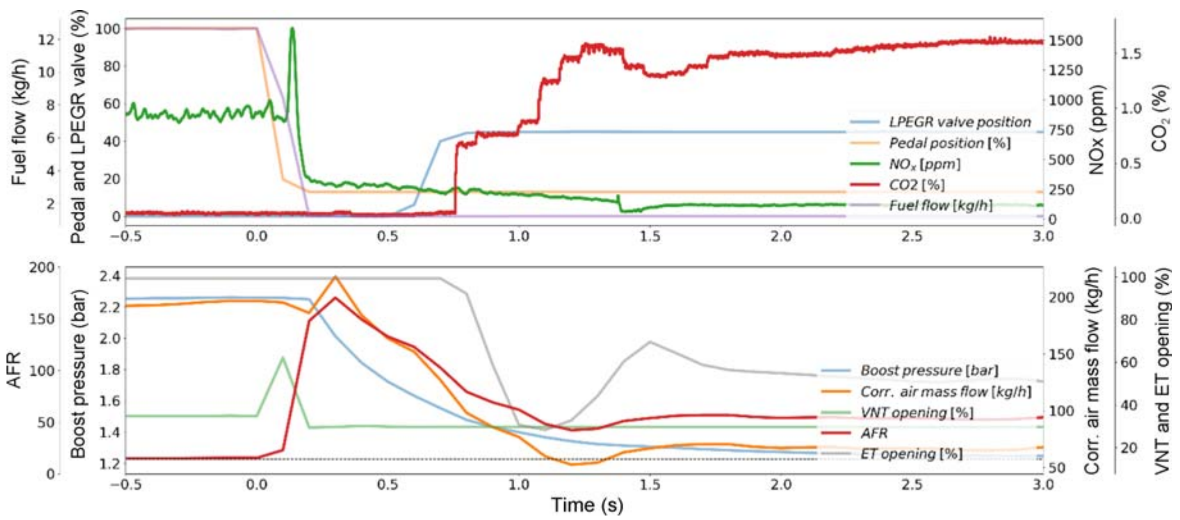

Figure 12. Measurements of different engine parameters and emission along with valve actuations during a typical Tip-In operation from low load to full load at 1500 RPM.

soon as the boost pressure target is achieved, the control moves the turbine positions to higher values regulating intake pressure. The time duration for the turbine to be almost closed is different for different engine speeds as the energy at the turbine inlet and turbine speed are different. This particular time decreases as the engine speed increases and it almost ends along with "waiting zone" as discussed in previous section. The calibrated smoke curbing AFR limit plays an important role for the torque generation during this period while the NOx is affected by the quantity of air (mainly oxygen) going inside the combustion chamber (Asad *et al*., 2014).

5.2. Transients with EGR

Recirculation of exhaust gases during transient operation by opening LP or HP EGR valve has a noticeable impact on NOx emissions. As seen in Figure 13, which shows the transient for 1500 RPM, the final steady state NOx levels at full load is reduced by almost around 50 % with LPEGR and 75 % with HPEGR configuration. From transient behavioral point of view, NOx concentration correlates with CO_2 concentration at the intake. The first stage of NOx evolution remains unchanged despite of any EGR strategy as emptying of exhaust gases in the intake circuit takes time (CO_2 concentration at the intake valve is similar with a configuration without EGR). Thereafter it reaches to the value for "waiting zone" and then to a final fixed (5 % rate) concentration. Before CO_2 concentration reaches to a fixed value, it has a slight dip representing a start of "waiting zone" (from the point where air starts increasing). This dip gets reflected as a peak in NOx concentration, which is detected in the middle plot of Figure 13. While in HPEGR strategy CO_2 arrives very fast and attains higher values due to high amount of EGR flow. Highly scattered values of CO_2 concentration explains the bad dispersion of HPEGR by the fact that exhaust gases and intake air are not properly mixed differing greatly from being homogeneous mixture at the location of NDIR500 probe. High amount of HPEGR flow arrives after sudden closing of VGT. Thereby increasing the pressure before turbine, driving a significant amount of exhaust gases through the HPEGR valve which was opened to the corresponding full load steady state condition with no similar VGT positions. Moreover, in the HPEGR case, the time for VGT remaining closed is also increased due to the fact that, the energy upstream the turbine is removed in the form of HPEGR flow and the VGT has to comply with reducing the area of the turbine to provide power to compressor. Clearly, the current turbocharger is not designed to work with HPEGR at full load, and therefore the performance is worse with this configuration.

From the performance point of view, HPEGR configuration takes more than 3 seconds to achieve the final boost pressure owing to the energy reduction before turbine even though the VGT is fully closed (see Figure 14). As a result, the torque gets diminished due to lack of air and proves that this configuration is not well suited in terms of vehicle dynamics. On the other hand, comparing with HPEGR configuration, LPEGR shows better results without losing much energy before turbine, which allows to increase the flow through compressor. Figure 14 (middle plot) shows LPEGR boost pressure evolution is quiet close to the one with the configuration without EGR. The engine torque (top plot) shows major difference only in the first

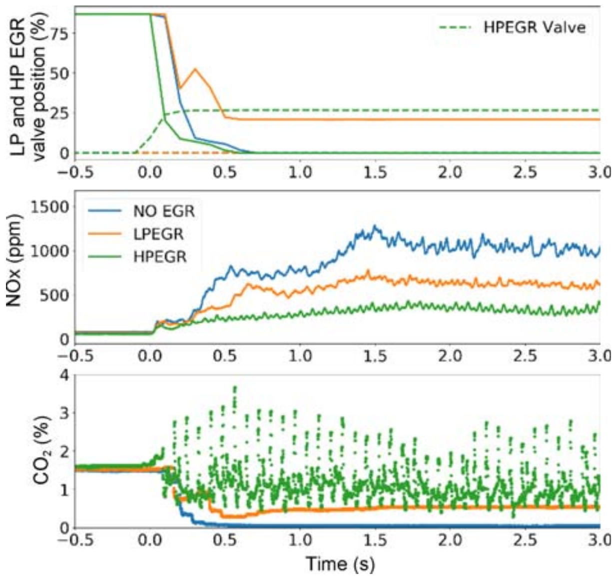

Figure 13. HPEGR and LPEGR valve positions with respective strategies along with the instantaneous NOx and CO_2 measurement during a harsh transient Tip-In operation at 1500 RPM (Dotted line: HPEGR valve; Solid line: LPEGR valve).

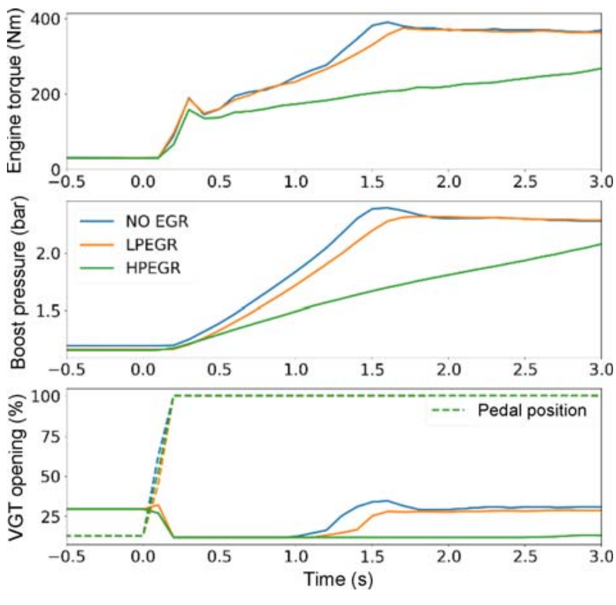

Figure 14. Performance of turbocharger and engine during load transient (Tip-In) at 1500 RPM with different EGR strategies.

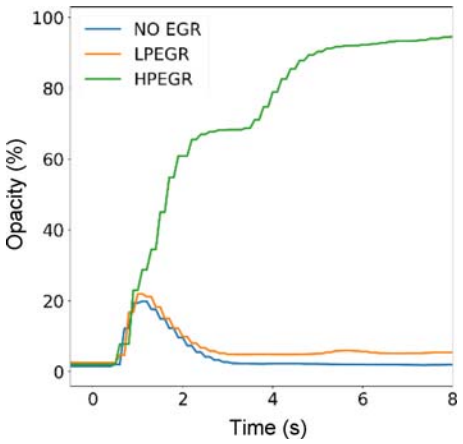

Figure 15. Opacity measurement at the exhaust after turbine during a load transient (Tip-In) at 1750 RPM with different EGR strategies.

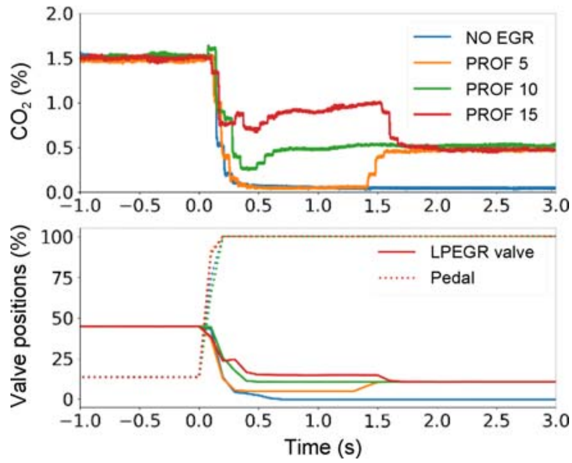

Figure 16. LPEGR valve movement and arrival of CO_2 at the intake valve of engine during a load transient (Tip-In) operation at 1750 RPM with different valve profiles.

few seconds of transients (during the "waiting zone") as the final torque is slightly reduced with 5 % EGR rate. Hence, performance wise, LPEGR is better than HPEGR. Moreover, we can also deduce that a control design of LPEGR configuration is simpler than HPEGR, for transient operations, with just the difficulty of the slight CO_2 transport delay in the intake line, which should be taken into account.

As stated earlier, the smoke limiting strategy has already been reached with 5 % EGR rate for all engine speeds except 1750 RPM. The opacity measurement for 1750 RPM are presented in Figure 15. Irrespective to the configuration, the rising part is almost similar while further opacity increases with the presence of EGR. The comparison with HP and LP EGR is difficult as the quantity of HPEGR in the initial phase is very high. The measured soot concentration for LPEGR strategy is higher than the one without EGR which can be improved by the smoke air-fuel limit.

5.3. Transients with Different Valve Profiles

Successful reduction of NOx with LPEGR strategy without losing significantly the engine performance leaded to another study to reduce those peaks at the start of the "waiting zone", which are results of first dip in CO_2 concentration. Different profiles for LPEGR valve with variation of 5 % were used before reaching to the final steady state value prescribed for full load to provide 5 % of EGR rate. The profiles are indicated as "prof5", "prof10" and "prof15" for 5 %, 10 %, and 15 % opening of valve respectively for that period. Figure 16 shows the arrival of CO_2 at the intake valve during transients for the different valve profiles used for 1750 RPM; At this engine speed "prof5" LPEGR valve position has no noticeable amount of burned gas flowing in the intake circuit. The corresponding engine torque and emission behavior during the above parametric tests are plotted in Figure 17.

Direct effect of change in intake CO_2 concentration can be detected in the "waiting zone" NOx concentration, while the performance in the form of engine torque is not reduced significantly during the first few seconds. To quantify these losses within these different profiles for the particular period of time during the transient operation, the area under the curve is calculated dividing by the specific time required to stabilize the performance as per the engine speed to obtain the average cumulative performance during respective transient operation. Area under the curve of engine torque after first random ascend introduced by the dynamometer and the acquisition frequency until the end of

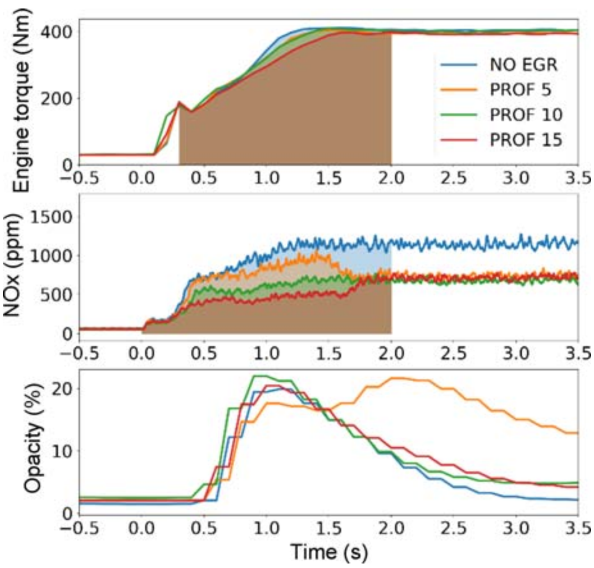

Figure 17. Performance and emission evaluation of a load transient at 1750 RPM during first few seconds with different LPEGR valve profiles.

Table 2. Evaluation time for performance during transient operation at different engine speeds.

Speed	1250	1500	1750	2000
Time	3s	2.5s	2s	1.5s

waiting zone has been calculated and further divided by time interval. The same procedure has been used for emissions until stabilization after the pedal has been pushed. The corresponding time intervals for each engine speed are detailed in the Table 2.

Figure 18 shows the breakdown of the NOx raw emissions, engine torque and opacity change in percentage from the base calibration during transient operation for different engine speeds. Four plots represent each engine speed with the concentration changes for opacity and NOx prominently with extent of LPEGR valve opening during the first seconds of a transient operation. Increase in valve opening reduces the NOx proportionally while torque on the other hand has a complex behavior. The torque loss is higher for “prof5” and “prof15” than “prof10” due to the boost control (variable geometry turbine). The VGT closes as soon as pedal is pushed and remains closed for longer period in case of transient EGR compared to without EGR. “Prof10” operation attains the boost pressure setpoint faster (moving the point to higher efficiency zone on compressor map) than the other 2 profiles. It causes opening of the VGT earlier, releasing the backpressure built up in exhaust manifold and resulting in better torque evolution. A proper value can be find at each engine speed for the LPEGR control to have minimum torque loss and maximum reduction in pollutant formation.

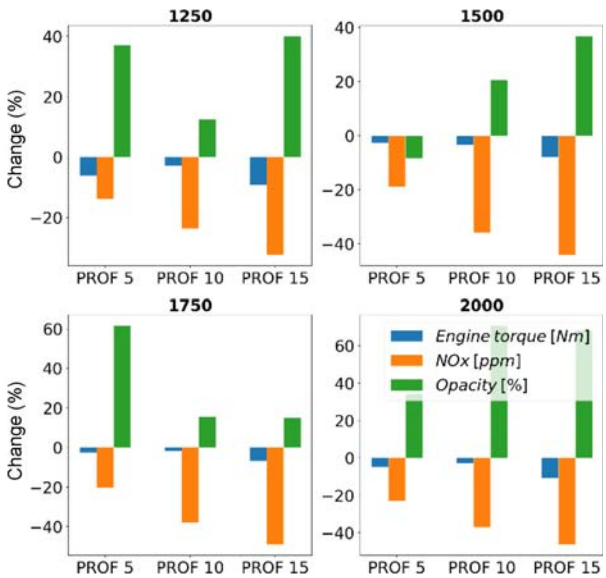

Figure 18. Performance and emission trade-off at different engine speeds during first seconds of a load transient operation.

5.4. Transient in a Roundabout Drive-through

The typical harsh transient, the engine has to face when a vehicle arrives at a roundabout on conventional roads is also carried out on a dynamic test bench with the same engine. It starts with almost partial load and goes to absolutely no load during the circular phase of the road, where the fuel is cut off for certain period of time and at the roundabout outlet, we have a sudden push of pedal to almost full load. In the testing campaign, these kind of operation were performed with 1500 RPM and the time for the fuel cut-off (engine cracking phase) was around 4 seconds. No matter the EGR valve position or configuration, no burned gas flows in the engine circuits in those 4 seconds. So when pedal is shifted to 100 % the flow of gases are not as same as in the Tip-In transient operation described in the previous section. Figure 19 shows the valve movements during these types of roundabout transients. As explained above, during cranking the intake line carries only air even in the EGR duct so there is no CO_2 concentration detected (apart from CO_2 in air). When the pedal is pushed, the arrival of CO_2 to the intake manifold is delayed for about half a second in the LPEGR configuration.

Although the arrival is delayed, no huge peak of NOx is observed after turbine. On the contrary, in the case of HPEGR configuration, the arrival is immediate. In order to counteract the delay in LPEGR, the HPEGR valve is opened for a second at the same time with LPEGR valve at the start of a transient. This configuration is called as “HP-LP” in the figures.

As the turbocharger is not designed for the energy reduction through HPEGR line flow before the turbine at higher loads, engine performance is heavily reduced with

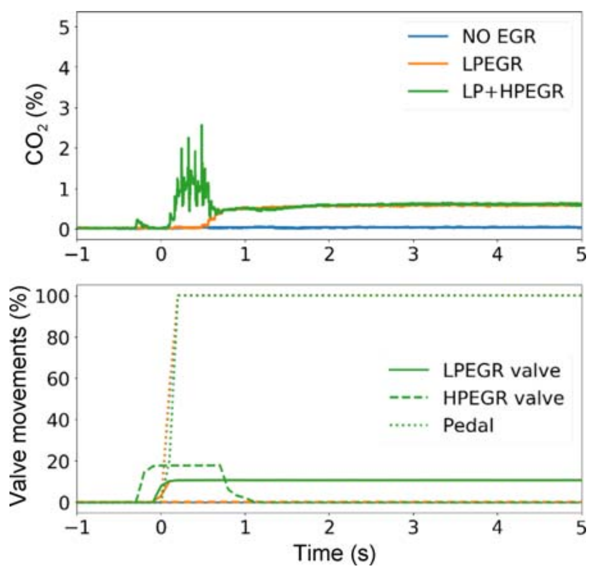

Figure 19. EGR valve actuation and CO_2 at the intake valve of an engine during a typical roundabout drive-through at 1500 RPM with different EGR strategies.

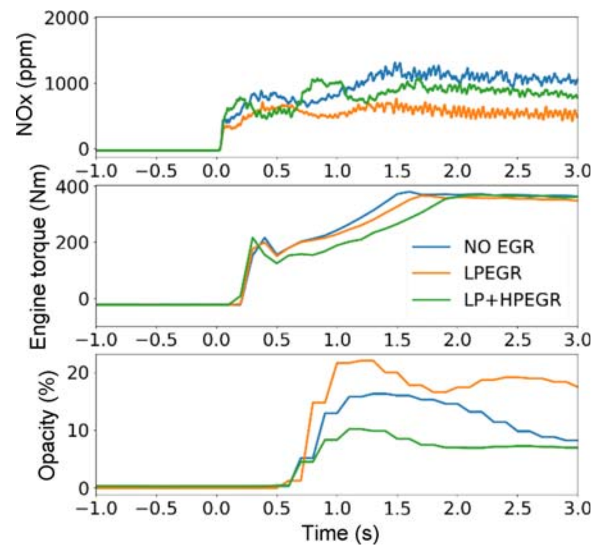

Figure 20. Emission and performance of an engine during a typical roundabout drive-through at 1500 RPM with different EGR strategies.

the opening of HPEGR valve for even a short interval of time. The total fuel injection went down with lack of air driven by the turbocharger and that is why the opacity is also seen to be reduced as compared to the basic operation without EGR in Figure 20. Moreover, the application of LPEGR at full load reduces the NOx by 50 % during this typical and harsh roundabout transient too where there is no EGR at the start with very limited impact in the engine torque.

6. CONCLUSION

Highly dynamic driving cycles like WLTC and RDE have been analyzed to study the impact on the EGR system operation. One RDE cycle was measured on a vehicle, plus further 90 cycles simulated with TNO's algorithm based on Markov chains. Two harsh transient operations during the cycles have been analyzed: load change at nearly constant engine speed with engaged gear shift (referred as load transients) and load/speed variations due to a gear shift (referred as speed transient). The cycle analysis shows that the load transients are found to be frequent in both WLTC and RDEs, and more repeated than speed transients. Also, the WLTC cycle has generally more harsh transient operations per unit time than the RDE cycles.

Focusing on the load transients, which are more challenging with respect to the EGR management, an analysis of the BMEP variation has been carried out. The number of harsh Tip-Out operations with absolute change in BMEP greater than 5 bar is always higher than harsh Tip-In transients in both WLTC and RDE cycles. Around 85 % load transient Tip-In operations occur in the range of 1000 ~ 2000 rpm. As for Tip-outs, almost 80 % are included in that range, and 60 % is concentrated in the range 1500 ~ 2000 rpm. In general, Tip-Out operations are more spread over the higher engine speed range than Tip-Ins. During WLTC, most harsh Tip-Ins occur around 1250 rpm, while in RDE they spread in the range from 1000 to 2000 rpm.

A high response time gas analyzer is more useful to measure the NOx emission during transient operation than the traditional slow analyser. The fast analyzer allows to capture the NOx peaks resulted from delays in air, fuel and EGR flow.

At full load, recirculation of exhaust gases reduce the NOx emissions considerably. The same rate of HPEGR and LPEGR providing same engine torque and opacity. However, they show different NO_x formation. LPEGR mixes very well with the air reducing the temperature of the combustion and the NO_x formation as compared to HPEGR. Moreover, it is evident that, unlike in precedent standards following NEDC, the usage of EGR all over the engine map is necessary.

During transients, HPEGR needs proper designing of turbocharger and VGT control during transient operations as the movement of VGT has direct impact on the pressure upstream of turbine and thus the HPEGR flow. Moreover, LPEGR rate is easier to control during load transients. From the transportation point of view, although HPEGR is faster than LPEGR, it is not critical for NOx emissions considering the fact of using EGR all over the engine map (including full load operation).

The optimization of LPEGR valve positions (profile) during transient operations (different than steady state operation) is required with specific turbocharger selection to give fast torque evolution, as LPEGR changes the mass flow rate through compressor and hence affecting the boost control which determines the back pressure in the exhaust manifold.

Considering “roundabout” transient with no EGR at the beginning of the maneuver, An EGR strategy to avoid the LPEGR lag could be the combination of LPEGR and HPEGR only during the lag time. The tests results show a good control of CO_2 during the transient for this strategy, however they also show a penalty in torque evolution due to the use of HPEGR.

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