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Master of Science in Mechanical Engineering

Master Thesis

Experimental tests for the after treatment system validation of an off road diesel engine

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Abstract

This Master Thesis deals with experimental tests performed to validate the after treatment system of a Kohler KDI 3404 diesel engine used on off-road applications, such us agricultural or earth-moving machines. In the first chapter is given an overview on the main characteristics of Diesel engines. The pollutant substances emitted by these systems and the emission limits adopted, over the course of the years, in Europe and USA, are presented in chapter 2. The experimental tests performed on the after treatment system are presented in chapters 3, 4, 5. In particular in the third chapter the fine-tuning of the DeSOx strategy, acting on the SCR system of a Tier4 KDI 3404 engine, is analyzed. This model was already defined inside the control unit software, but it has been important to refine the temperature thresholds at which the DeSOx strategy is activated and the SOx model desorption rates, in order to reach a better alignement with experimental data and to ensure the best regeneration on the working field. Tests presented in the fourth chapter has been done to study how the DOC and DPF systems works together, on a KDI 3404 Stage V, with the aim of understanding the soot accumulation behaviour on the DPF filter. Different working cycles, such as NRTC transient and low load, has been performed at the dyno-brake to obtain soot balance points. Finally the fifth chapter is focused on the analysis and characterisation of possible urea deposits inside SCR of a KDI 3404 Stage V engine. In the last part of the work the conclusions about the usefulness of these activities, with respect to after treatment system development, are explained.

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Introduction

During these years the theme of climate change with the connected topics of global warming and pollutant emissions are two constant that daily affect our life. It is known that CO_2, substance emitted by internal combustion engines and classified as climate-change gas, is the main responsable of this effect on climate, while primary pollutant, such as CO, HC, NO_x and PM, are responsable for the pollution that affect our cities.

Why, therefore, we are still analyzing and working on internal combustion engines? In the automotive world hybrid and electric propulsion systems are emerging and are becoming more accesible to all vehicle level and orientation. On the other side, in heavy duty industry, engines have to fulfill different requirements in power delivery. As a consequence a general electrification of the powertrain is unsatisfactory and not feasible. At the same time the pollutant standard is becoming, both for the European and USA legislation, but also for the Chinese one, year by year more severe and difficult to fulfill. In order to comply with these new standards, heavy duty industries have to study and introduce new exhuast gas after treatment technologies, such as DPF or SCR system, that result completely new to this sector. The work performed in this thesis falls under this perspective. On the one hand the activity is focused on the improvement of the SCR working operation that tends to be poisoned by sulfur. The goal is to refine the desulfurization strategy acting on the SCR system mounted on Kohler KDI 3404 Tier 4 Final. Others studies are developed on the DPF and SCR system installed on Kohler 3404 Stage V. In this case for what concern DPF a first analysis on soot accumulation behaviour, on different engine working cycles, is performed, with the main goal of defining soot balance points. On the same after treatment system the analysis proceeds by exploring possible urea deposits inside the SCR system when the engine works in specific operating points with a critical urea dosing amount. The objective is to set new urea limits in the dosing map.

1 Diesel engine characteristics

The diesel engine is classified as compression-ignition system in which the fuel and air are mixed inside the combustion chamber, where the latter, required for combustion, is highly compressed. The compression phase generates high temperatures which are sufficient for diesel fuel to spontaneously ignite when it is injected into the cyclinder. The chemical energy contained inside the fuel is released and converted into mechanical force.

Diesel engines can contain one or more cylinders, with the piston inside that perform up and down movements driven by combustion of air/fuel mixture.

This operating method gives to this system the name of ”reciprocating-piston engine”.

In figure 1.1 is reported a general scheme of the main components that form the diesel engine.

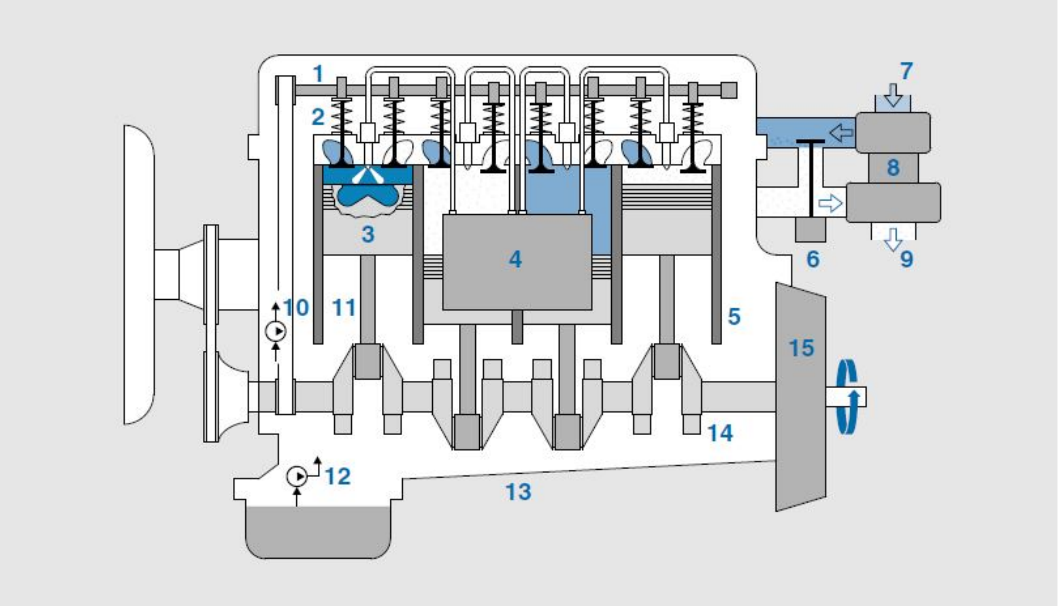


Figure 1.1: Four cylinders diesel engine

The connecting rod (11) is the element that converts the linear reciprocating action of the piston (3) into rotational motion of the crankshaft (14). A flywheel (15) is attached at one end of (14) and it helps to mantain continuous crankshaft rotation and reduce irregularities caused by the period nature of combustion inside each cylinder (5).

The camshaft (1) manages the time opening and closure of intake and exhaust valve system. This operations is fundamental in order to correctly put air inside the cylinder during the introduction stroke and evaquate burned gases during the exhaust stroke. (4) indicates the fuel-injection system that can be of different types but in every case has the main goal of introducing fuel inside the combustion chamber. An exhaust-gas recirculation system can be present in correspondence of the intake manifold (7) with the main goal of reducing NO_x emissions. Diesel engines are particularly suited to aspiration by means of a turbocharger or supercharger (8). These devices not only have the goal of increasing engine power and efficiency, but also to reduce pollutant emissions and combustion noise. The exhaust emissions are taken to the after treatment system by using the exhaust pipe (9). Due to thermal loads developed by the combustion process it is important to keep the engine working temperature under controll. This is realized by means of a cooling system fed by a cooling pump (10). The same importance has the lubricating system (12) that has the goal of keeping, as much as possible, smooth the motion of each mehanical part.

Until now the main components that constitute an engine has been presented but no informations have been showed to explain how the chemical energy contained inside the fuel is transfromed into mechanical force. In order to do this in figure 1.2 is reported the typical operating cycle of a four stroke diesel engine.

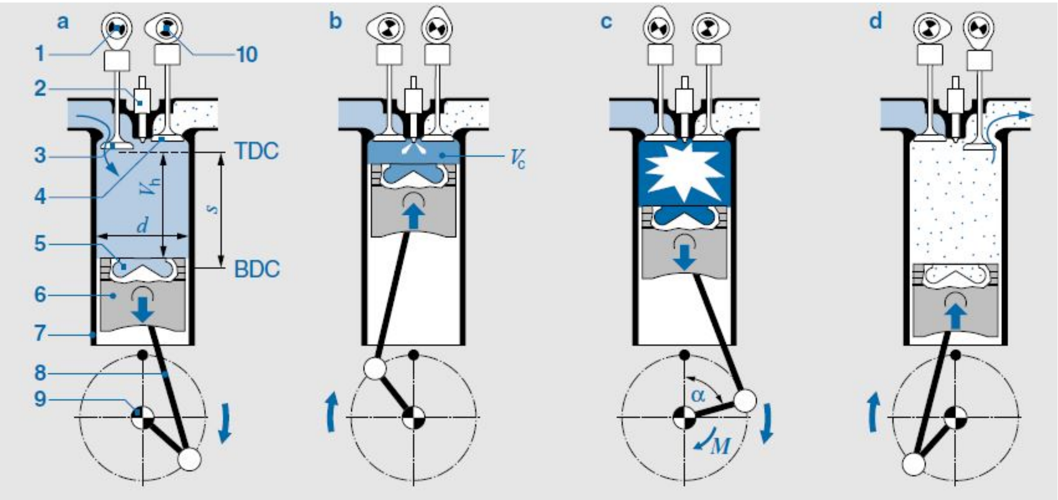


Figure 1.2: Four stroke Diesel engine operating cycle

By analyzing what happens in a single cyclinder of the engine presented in figure 1.1, during the induction stroke (a) the inlet valve is opened thanks the camshaft rotation , while the outlet valve is fully closed(it is important to notice that the camshaft can directly act on the valve system, but in other cases there is a kinematics system in between). The piston moves from the TDC (Top Dead center) to the BDC (Bottom Dead Center) increasing the capacity of the cylinder. The compression stroke (b) represents the phase in which the piston motion towards the TDC compress the air trapped inside the cylinder to the degree determined by the engine's compression ratio, that can vary from 6:1 in large scale engines to 24:1 in car engines. At the end of the compression stroke air can reach 900 °C. This is the ideal condition for the fuel-injection system to to introduce fuel inside the combustion chamber (the injection pressure level can vary between different types of engines but as order of magnitude can be assumed thousands of bar). When the ignition lag is crossed the ignition stoke (c) begins. The atomized fuel combustion increases further the temperature and pressure levels and the amont of energy released depends on the mass of the fuel injected. With both the inlet and outlet valves closed, the pressure forces the piston downwards. Thus during this phase the chemical energy released by combustion is converted into piston kinetic energy. Thanks to the crankshaft, the latter is converted into torque (turning force). When the piston concludes the ignition stroke and it is near the BDC the exhaust valve opens and the hot, pressurized gases flow out of the cylinder (d). During the upwards movement of the piston the remaining exhaust gases are expelled. At the end of the exhaust stroke the crankshaft has performed two revolution and a new operating cycle can start with the induction stroke.

2 Diesel Engine pollutant emissions

2.1 General Overview

In this section a general overview on pollutant emissions and on the after system treatment is given. As a general definition compression ignition engines are characterized by a mixture that is generally lean, this means that the air to fuel ratio is higher than the stoichiometric value (λ=14,6). In reality it is important to underline that the air to fuel mixture is strongly inhomogeneous, as a consequence it is possible to find combustion chamber zones with different chemical composition. This point is crucial in order to understand the main pollutant emission mechanisms formation. In addition, due to temperature grandient over the cylinder section, the combustion process cannot proceed correctly to the complete hydrocarbons oxidation.
The pollutant molecules on which it is important to focus the attention are:

1. Carbon monoxide (CO)
2. Unburned Hydrocarbons (HC)
3. Nitogen Oxides (NO_x)
4. Particulate Matter (PM)
5. Sulfur Dioxide (SO_2)

2.1.1 Carbon Monoxide

Carbon Monoxide is an intermediate product deriving from hydrocarbons oxidation process. Reaction zones with an high temperature level are the ideal formation areas. The chemical transformations from hydrocarbons to carbon monoxide are fast reactions. Once the CO is formed there are two chemical reactions, strongly dependet on temperature, that regulate the balance with CO_2:

$$CO + OH \longleftrightarrow CO_2 + H \tag{1}$$

$$CO_2 + O \longleftrightarrow CO + O_2 \tag{2}$$

Due to slow chemical kinetics of (1) (2) and, on the other hand, fast expansion phase that generate a temperature drop , chemical transformations result as freezed to the CO reactant side. The use of lean mixtures in Diesel engines makes the CO levels to be one order of magnitude lower than the ones emitted from spark ignition engines. The inhomogeneous conditions cause anyway the local formation of non negligible amounts of CO in the richest mixture zones.

2.1.2 Unburned Hydrocarbons

Hydrocarbons are the consequence of incomplete combustion of the hydrocarbon fuel. Their formation can derive from unburned fuel that is trapped within infinitesimal combustion chamber volumes, called crevices, oil layer adsorption and desorption, flame quenching caused by colder cylinder walls or not sufficient thermal energy of the mixture zone involved in the combustion process. The inhomogeneous conditions give also their contribution to the unburned hydrocarbons formation: HC form in the zone close to the spray boundary where the fuel has already mixed beyond the lean limit of combustion (overleaning phenomena) and it not able to autoignite or sustain a fast reaction front. On the other hand central regions of the jet present rich mixtures and lack of oxygen in quantities needed for oxidation reactions completion. Last but not least non negligible source of HC derives from undermixing of fuel which leaves the injector nozzle at low velocity, late with respect to the combustion process.

2.1.3 Nitrogen oxides

Nitric oxide (NO) and nitrogen oxide (NO_2) are usually grouped together as NO_x emissions. NO formation derives from oxidation of atmospheric nitrogen. It has been accepted that in near stoichiometric air to fuel mixtures the principal reactions governing NO formation are

$$O + N_2 \longleftrightarrow NO + N \tag{3}$$

$$N + O_2 \longleftrightarrow NO + O \tag{4}$$

$$N + OH \longleftrightarrow NO + H \tag{5}$$

Moreover, knowing that in CI engines NO_2 contribute is not negligible, approximately 30 % of $\frac{NO_2}{NO}$ ratio, a plausible formation mechanism is

$$NO + HO_2 \rightarrow NO_2 + OH \tag{6}$$

Subsequently the inverse reaction is possible

$$NO_2 + O \rightarrow NO + O_2 \tag{7}$$

unless the NO_2 formed is quenched by mixing with cooler air. Generally, NO_x form inside the reaction zone where a high temperature level promote the reaction of the oxygen excess with nitrogen. In particular mixture which burns in the first phases of the combustion process is important because it is compressed to a higher temperature as combustion proceeds and cylinder pressure increases. After the peak pressure, burned gases decreases their temperature due to cylinder gases expansion. This phenomena leads to NO decomposition freezing.

2.1.4 Particulate matter

Diesel particulates is formed by combustion generated carbonaceous material (soot) on which organic compounds have become absorbed. Most particulate material results from incomplete combustion of fuel hydrocarbons, some is contributed by the lubricating oil.
The composition of the particulate material depends on the conditions in the engine exhaust and particulate collection system. With temperatures higher than 500 °C the individual particles are formed by clusters of small carbon spherules (with a small amount of hydrogen). As temperature decrease below 500 °C on particles, due to adsorption and condensation process, can be founded high molecular weight organic compounds which include: unburned hydrocarbons, oxygenated hydrocarbons (ketones, esters, ethers, organic acids) and polynuclear aromatic hydrocarbons. The condensed material includes also inorganic species such as sulfur dioxide, nitrogen dioxide, and sulfuric acid (sulfates).
Particle matter is overall formed in the central regions of the fuel jet, strongly rich zones in which the fuel burns in diffusive flames. The following mixing with surrounding air (at the end of the injection) enhances a partial oxidation of the carbonaceous nuclei. A good level of turbulence could guarantee the remixing with oxygen present in the cylinder and so a partial oxidation of particle matter. Getting closer to the exhaust valve opening, cylinder temperature decreases and oxidation reactions slow down. Soot levels are then still high and the gas treatment downstream of the engine becomes fundamental.

2.2 Exhaust gas tretament

In the past years diesel emissions were treated only by using implemented sytems inside of the engine, such us EGR system. With the increase of severity of emission limits, also in the off-road engines regulation,it has been fundamental to use combination of measures inside and downstream of the engine. This is the reason why exhaust gas treatment started to be used.

2.2.1 Diesel oxidation catalyst

The Diesel oxidation catalyst involves different functions for exhaust gas treatment. In particulat it is used to reduce CO and HC emissions (both as single subastances and particle mass), to oxidate NO in order to form NO_2. Finally it helps to increase exhaust gas temperature being used as catalytic burner.
The oxidation of carbon monoxide (CO) in (8) and hydrocarbons (HC) in (9) produces carbon dioxide (CO_2) and water vapour (H_2O). This reaction is completed starting from a specific temperature threshold, defined as lightoff temperature. Depending on exhaust gas composition, flow velocity and catalyst composition the lightoff temperature takes place at about 170 °C to 200 °C.

$$C_nH_{2m} + (n + m/2)O_2 \rightarrow nCO_2 + mH_2O \tag{8}$$

$$CO + 1/2O_2 \rightarrow CO_2 \tag{9}$$

Another activity performed by the DOC takes to reduction of particulate mass emission, due to oxidation of soluble organic fraction placed on particulate matter.
The NO_2 generation is another main goal of DOC. NO_2 is fundamental for downstream components such us particulate filter, due to the fact that at low temperatures NO_2 is a more active soot oxidize than O_2. NO_2 is in a temperature equlibrium with NO in presence of oxygen: at low temperatures (<250 °C) the equilibrium is shifted towards NO_2 while above 450 °C NO is dominant. The DOC function is to rise NO_2/NO at low temperatures by inducing thermodynamic equlibrium. The last function of the DOC is to create a sort of catalytic burner: during DPF regeneration phase is necessary to increase exhaust gas temperatures. The heat relased comes from CO and HC exothermic reactions. HC and CO emissions are specificcaly raised by using secondary fuel injections (commonly known as after injections).

From the constructive point of view the DOC is made by a carrier structure of ceramics or metal material. On this frame can be found a washcoat composed of aluminium oxide (Al_2O_3), cerium oxide (CeO_2), zirconium oxide (ZrO_2), with active catalytic noble metals, (Palladium (Pd), Platinum (Pt)), quantified as g/ft^3, dispersed inside. The main functions of the washcoat structure are to provide a larger contact area for the noble metals and to avoid catalyst sintering at high temperatures. Eventualy differences in the structural design and different catalyst composition affects DOC properties such as lightoff temperature, conversion efficiency and tolerance to poisoning. The main parameters that are used to characterize the internal structure are the channel density, specified as cspi (channel per square inch), the wall thickness of a single channel and the external dimension of the catalytic converter. The first two parameters affects the heat up response and the exhaust gas backpressure. In the choice of the DOC volume is usually adopted V_{cat}/V_{stroke}=0,6-0,8. Eventually it is important to notice that with high temperatures sintering process can happen. The new larger catalytic spherules, that are formed with a smaller active surface area, cause a decrease of the DOC efficiency.

2.2.2 Diesel particulate filter

Soot particles emitted by the engine are efficiently removed by using a filter of porous ceramics. These filters, with a honey-comb structure, are made by silicon carbide (Cordierite) and are formed by parallel and square channels. Each channel can be closed at the inlet or outlet side of the filter, so that the ceramic plugs at the inlet force the exhaust gas to penetrate through the porous ceramic walls. The soot particles have two types of contact with the walls: they can be transported into the pore walls, by diffusion, where they adhere (deep-bed filtration) or they are stored on the surface of ceramic walls (surface filtration). Following the first accumulation method, a layer of soot (defined soot cake) forms on channels walls. This fact guarantee an highly

efficient surface filtration for the following operating phase. It is not convenient from the point of view of exhaust gas backpressure to have a too thick soot layer, therefore a regeneration strategy must be considered.
With the concept of regeneration is indicated the strategy that has as result the particle carbon component oxidation by using oxygen constantly present in the exhaust gas above 600 °C. Another type of regeneration can be realized at lower temperatures by using NO_2 as oxidizer. This method is known as continuously regeneration.
Due to difficulties to obtain high temperatures (600 °C) during normal engine conditions, the soot oxidation can be lowered to 450-500 °C by using an additive (cerium or iron compounds) into the fuel. Another soot particles burnoff can be obtained by coating the filter with noble metals (mainly platinum). All these techniques helps the regeneration procedure, but not always the minimum exhaust gas threshold temperatures are reached. Therefore an active regeneration is implemented, by changing the combustion control, in order to rise the exhaust gas temperature to soot burnoff level.

2.2.3 SCR system

SCR system allows to reduce nitrogen oxides (NO_x) in presence of oxygen using selected reducing agent. It is important to underline that with the term of "*selective*" is indicated the reducing agent that prefers to oxidize the oxygen contained in the nitrogen oxides instead of with the molecular oxygen present in exhaust gas. Ammonia (NH_3) is a substance that present this selective reducing characteristic.
Due to toxicity NH_3 is produced from nontoxic carrier substance, such as urea. This one is produced on industrial scale and it is chemically stable. Being soluble into water, it is introduced in exhaust gas by an urea/water solution.
Ammonia (NH_3) is produced from urea before the SCR reaction start. This happens through two reactions: the first one is a thermolysis reaction (10) that produce isocyanic acid and ammonia:

$$(NH_2)_2CO \rightarrow NH_3 + HNCO \tag{10}$$

In the second reaction isocyanic acid is converted with water (hydrolisis reaction) and is formed ammonia e carbon dioxide (11):

$$HNCO + H_2O \rightarrow NH_3 + CO_2 \tag{11}$$

The reaction (11) has to be realized rapidly in order to avoid precipitation of solids. This is obtained by using suitable catalysts and temperatures that are higher than 250 °C. Ammonia produced in (10) and (11) reacts in the catalytic converter according to the following equations:

$$4\ NO + 4\ NH_3 + O_2 \rightarrow 4\ N_2 + 6\ H_2O \tag{12}$$

$$NO + NO_2 + 2NH_3 \rightarrow 2\ N_2 + 3\ H_2O \tag{13}$$

$$6\ NO_2 + 8\ NH_3 \rightarrow 7\ N_2 + 12\ H_2O \tag{14}$$

In order to prevent NH_3 leakage, that derives from a bad conversion of reducing agent, is placed an additional oxidation catalyst downstream of the SCR catalytic converter. This block helps to convert all the ammonia into N_2 and H_2O. New generation of SCR catalytic converters achieve a NO_x conversion rate higher than 0,5, only at temperatures above 250 °C (optimized conversion rates are obtained within 250 °C and 450 °C). Present research on catalytic converter is focused on optimizing activity at low temperatures.

3 Pollutant emissions regulation for Diesel Engine

3.1 General Overview

Starting from 1997 non-road engines word has been regulated with pollutant emissions limits.

In Europe the limits are imposed by the European community and has been labelled, over the course of the years, as ”Stage”. In the United States the emission limits are regulated by the Environmental Protection Agency (EPA) and are identified as ”Tier”.

In order to measure the emissions of a vehicle with the relative internal combustion engine and to certify the compliance of its behaviour in a standard way, in the automotive sector the whole system is tested on the dynamometric rollers. The vehicle follows a speed cycle , with prescribed gears inserted, along a certain period of time. The speed cycle should represent different working conditions that the vehicle could found during its usage.

In Europe ,from 1970 to 2015, with some updates through the years, the representative working cycle has been the NEDC (New European Driving Cycle): it is formed by four ”urban cycles” and one ”extra-urban cycle”, the gear profile is fixed with the possibility to use the sixth gear on the ”extra-urban phase”. Over the course of the year a strong discrepancy between real world driving conditions and type approval test (like the NEDC) has been appeared and so in order to reduce this gap , from 2017, WLTP (Worldwide harmonized Light vehicles Test Procedure) cycle has been introduced. The goal of this cycle was to create a driving test conditions closer to real ones , but also to introduce a cycle that could be used by all the countries in the world (this was the idea behind ”worldwide harmonized” label). The cycle contains a larger number of accelerations, an average speed higher than NEDC and less periods of time in idle conditions.

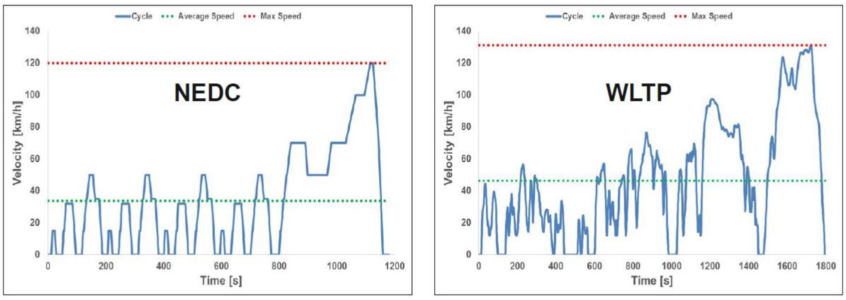


Figure 3.1: NEDC and WLTP cycles

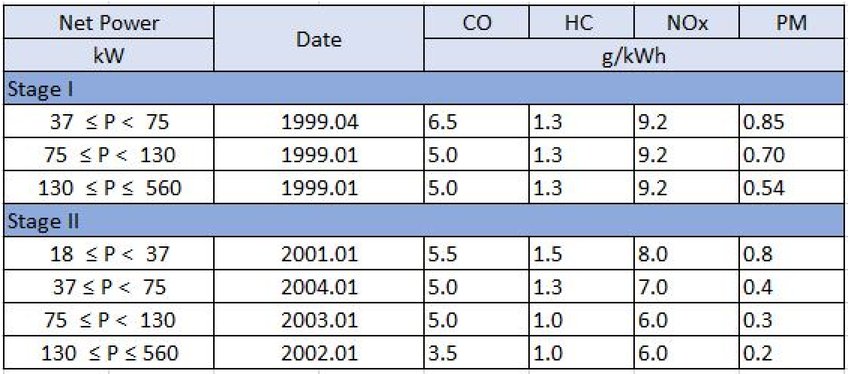
Differently in the off-road sector the entire vehicle is not tested on roller benches, due to the large number of different applications where the powertrains can be mounted . For these reasons the type approval procedure require that only the engine is tested on dyno brake, which control engine speed and absorb the delivered torque. Both transient and a stationary cycles are performed. Steady-state tests check the engine emissions in various operating points, while transient cycle are more severe because of their vary fast speed and load variations, simulating different kinds of vehicle application operations.

3.2 European standards

Over the past few years the emissions standard for non-road mobile machinery (NRMM) engines have been organized from Stage I to Stage V and the level of strictness has been incremented.
Stage I regulations was specified for the first time in Directive 97/68/EC, then from 2002 to 2012 five amending directives regulated the guideline until Stage IV standard. For what concern Stage V standard, Directive 97/68/EC and its amendments has been replaced with Regulation 2016/1628 that specified new emission requirements for all categories of compression ignition engines.
In order to have an idea on the principle steps of the European standards development it is possible to summarize the key points of their growth.

3.2.1 Stage I/II

Stage I, promulgated on December 16, 1997 and implemented in 1999, is the first European legislation to regulate emission for non-road mobile machines. Subsequently, from 2001 to 2004, Stage II was implemented depending on the engine power output.



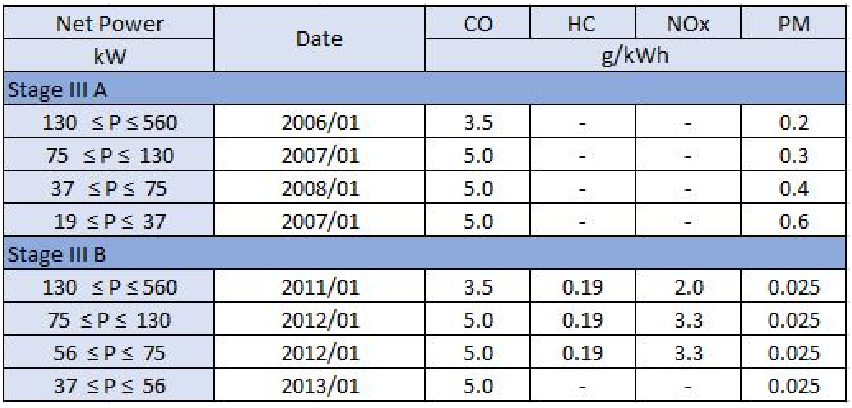
Net Power	Date	CO	HC	NOx	PM
kW		g/kWh			
Stage I					
37 ≤ P < 75	1999.04	6.5	1.3	9.2	0.85
75 ≤ P < 130	1999.01	5.0	1.3	9.2	0.70
130 ≤ P ≤ 560	1999.01	5.0	1.3	9.2	0.54
Stage II					
18 ≤ P < 37	2001.01	5.5	1.5	8.0	0.8
37 ≤ P < 75	2004.01	5.0	1.3	7.0	0.4
75 ≤ P < 130	2003.01	5.0	1.0	6.0	0.3
130 ≤ P ≤ 560	2002.01	3.5	1.0	6.0	0.2

Figure 3.2: Stage I/II Standards

The regulated equipment covered by these two first stages included industrial drilling rigs, compressors, construction wheel loaders, bulldozers, non-road trucks, highway excavators, forklift trucks, road maintenance equipment, snow plows. Agricultural and foresty tractors followed the same emissions standard but they had different implementation dates. Stage I/II didn't cover emissions of engines mounted in ships, railway locomotives, aircraft. For genereting sets Stage II applies from 2007.01.

3.2.2 Stage III/IV

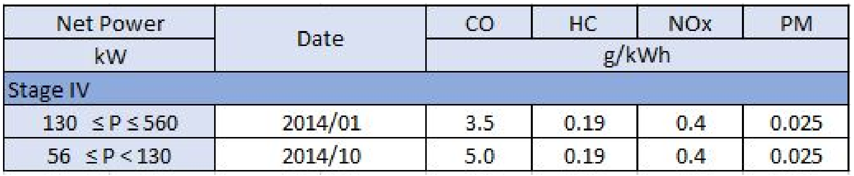
Stage III, which is subdivided into into Stage IIIA and IIIB, was phased-in from 2006 to 2013. Thereafter in 2014 Stage IV entered into force.
Stage III/IV standards, in addition to the engine categories regulated by Stage I/II covered railroad locomotive engines and marine engines and included a limit for ammonia emissions, fixing this value to 25 ppm as a mean to not exceed over the test cycle. Stage IIIB implemented a PM limit of 0.025 g/kWh in order to push the introduction of the DPF (Diesel particulate filter) technology, but most of the engines have been able to comply with this limit realizing a cleaner combustion that necessarily generate higher NO_x due to increased air introduction. In-cylinder systems, such as EGR technology, allow to limit NO_x production.



Net Power	Date	CO	HC	NOx	PM
kW		g/kWh			
Stage III A					
130 ≤P≤560	2006/01	3.5	-	-	0.2
75 ≤P≤ 130	2007/01	5.0	-	-	0.3
37 ≤P≤ 75	2008/01	5.0	-	-	0.4
19 ≤P≤ 37	2007/01	5.0	-	-	0.6
Stage III B					
130 ≤P≤560	2011/01	3.5	0.19	2.0	0.025
75 ≤P≤ 130	2012/01	5.0	0.19	3.3	0.025
56 ≤P≤ 75	2012/01	5.0	0.19	3.3	0.025
37 ≤P≤ 56	2013/01	5.0	-	-	0.025

Figure 3.3: Stage IIIA/IIIB Standards

In figure 3.3 it is possible to notice this change on PM limit. In Figure 3.4 are reported the limits imposed by Stage IV standards: it is possible to notice the introduction of very stringent limits on NOx emission: 0.4 g/kWh. This new threshold took to the use of NOx after-treatment system, typically urea-SCR.

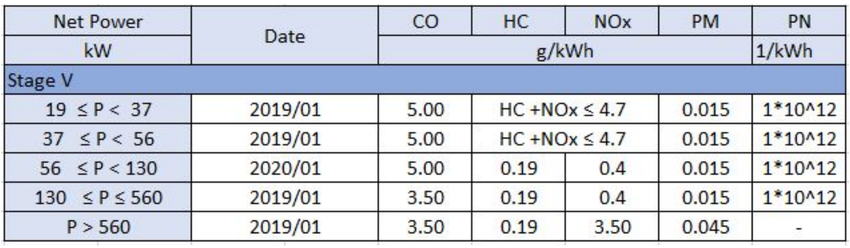


Net Power	Date	CO	HC	NOx	PM
kW		g/kWh			
Stage IV					
130 ≤P≤560	2014/01	3.5	0.19	0.4	0.025
56 ≤P<130	2014/10	5.0	0.19	0.4	0.025

Figure 3.4: Stage IV Standard

3.2.3 Stage V

Stage V regulation was proposed in 2014 and introduced on September 14, 2016. The standards are effective from 2019 for engines below 56 kW and above 130 kW and from 2020 for engines in the range 56-130 kW. In figure 3.5 are reported the emission limits.



Net Power	Date	CO	HC	NOx	PM	PN
kW		g/kWh				1/kWh
Stage V						
19 ≤ P < 37	2019/01	5.00	HC +NOx ≤ 4.7		0.015	1*10^12
37 ≤ P < 56	2019/01	5.00	HC +NOx ≤ 4.7		0.015	1*10^12
56 ≤ P < 130	2020/01	5.00	0.19	0.4	0.015	1*10^12
130 ≤ P ≤ 560	2019/01	3.50	0.19	0.4	0.015	1*10^12
P > 560	2019/01	3.50	0.19	3.50	0.045	-

Figure 3.5: Stage IV Standard

In this case differently from the previous standards a new limit for particle number emissions is introduced for engines between 19 kW and 560 kW. In order to comply with this new threshold a particle control technology is implemented using wall flow particle filters such as DPF.

The PM limit is 97 % lower respect Stage I standard (Figure 3.6), while the hydrocarbon (HC) plus nitrogen oxides (NO_x) limit is reduced of 94 % (Figure 3.7).

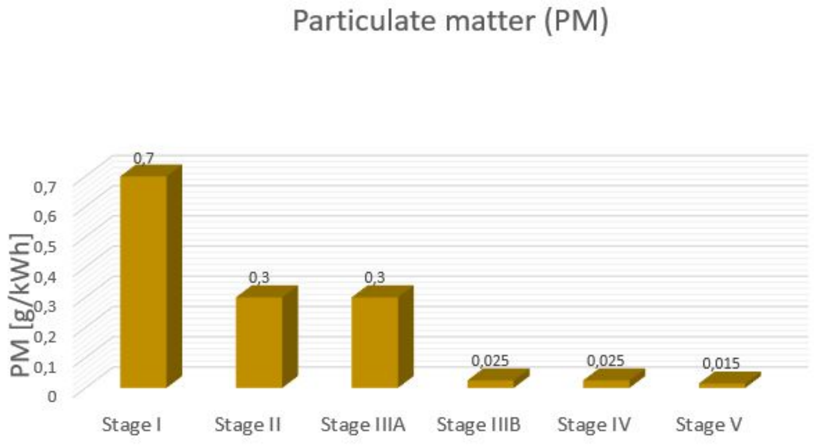


Figure 3.6: PM limits

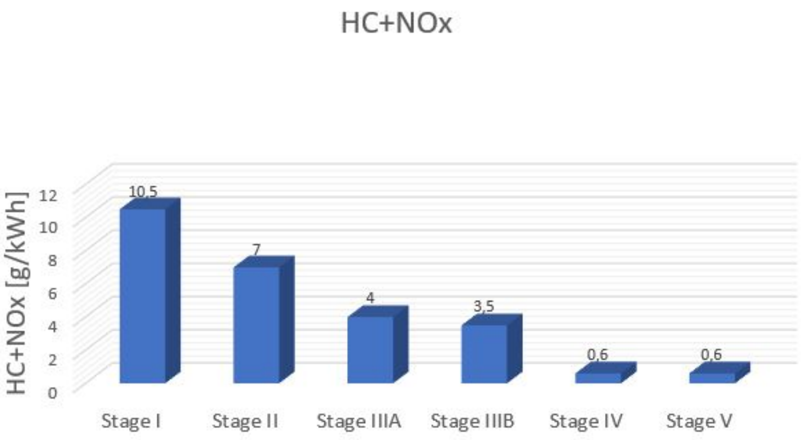
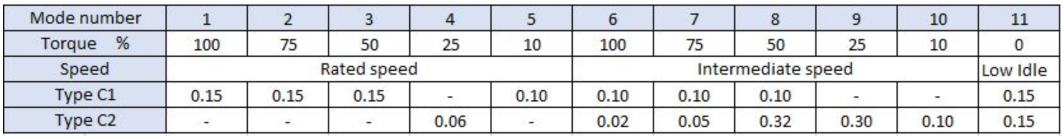


Figure 3.7: HC+NOx limits

Figure 3.6 and 3.7 shows emissions standards for engine with power range from 56 kW to 130 kW.

3.2.4 European test cycles

Stage I/II standards emissions were measured by using ISO 8178 C1 8 mode cycle and were expressed in g/kWh.
ISO 8178 is an international standard applied for exhaust emission measurament of non-road engines applications. It is used in Europe, United States and Japan. Depending on the legislation of each specific country, the type approval test cycle can be defined by reference to the ISO 8178 standard or, as happens in USA EPA regulation, by specifying a test equivalent to it in the national legislation.
The ISO 8178 contains A-types 13-mode cycle and B-types 11-mode cycle. With reference to the B-type standard there are steady-state engine dynamometer tests cycles, labelled as C1, C2, D1, D2 etc., depending on engine classes and equipment. With the simbol "C" are identified the steady-state cycles that are used to test off-road engines. Each of these cycles involves a series of weighted factors whose sum is equal to one. Type C1 cycle is also referred as Non-road stationary cycle (NRSC) and it contains 8 modes.



Mode number	1	2	3	4	5	6	7	8	9	10	11
Torque %	100	75	50	25	10	100	75	50	25	10	0
Speed	Rated speed					Intermediate speed					Low Idle
Type C1	0.15	0.15	0.15	-	0.10	0.10	0.10	0.10	-	-	0.15
Type C2	-	-	-	0.06	-	0.02	0.05	0.32	0.30	0.10	0.15

Figure 3.8: Non-road steady cycle

With the introduction of Stage III/IV standard a new transient test procedure, in cooperation with the US EPA, has been introduced to better represent emissions on what is identified as ”on-field” environment. In this case the test is performed as a transient cycle, differently from previous stationary test procedure. Another important reason that took to the introduction of a new dynamic test procedure was the desire to test engines similarly to what is simulated on automotive chassis dynamometers.
This cycle has been identified as Non-Road Transient Cycle (NRTC) and it has a duration of 1238 s, during which the engine performes hard accelerations and strong load variations, exploiting all its speeds and torque range from 0 % to 100% (Figure 3.9). NRTC test cycle is performed twice: with a cold and a hot start. With a cold start the engine cooling fluid is at ambient temperature, while the hot start is performed after a 20 minutes soak with the cooling fluid at about 90°. The final emission results are weighted averages of 10% for the cold start and 90% for the hot start run. The new cycle was used in parallel with the prior Non-road stationary cycle (NRSC).

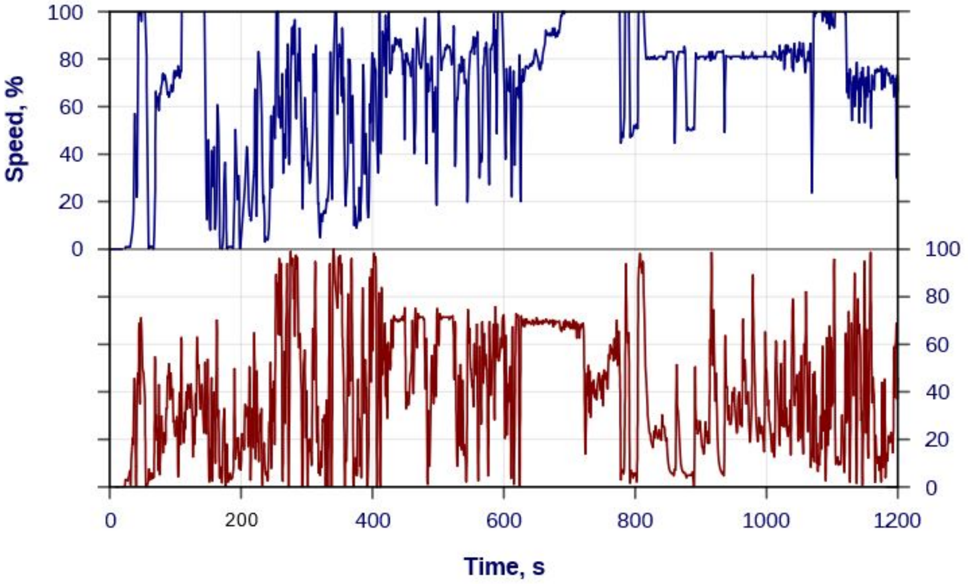
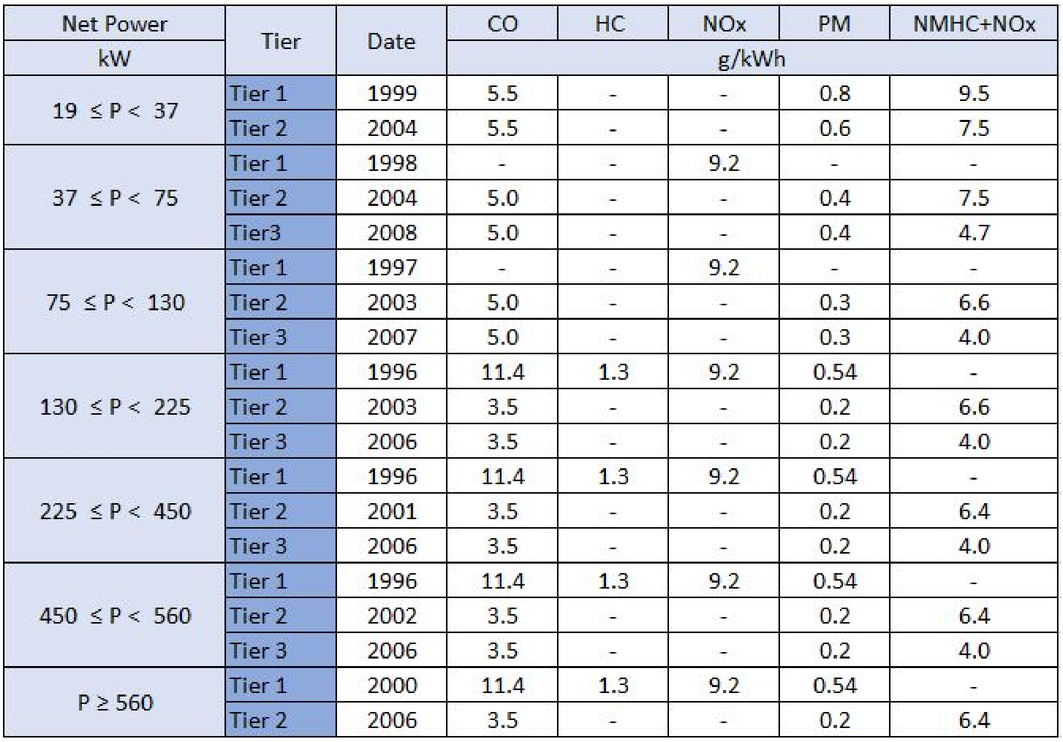


Figure 3.9: Normalized Speed and Torque NRTC profile

3.3 United States Standards

In 1994 the first federal standards (Tier 1) for non-road machines, with power higher than 37 kW, were adopted, to be phased in from 1996 to 2000. Following the SOP (Statement of Principles), signed in 1996 between EPA, California

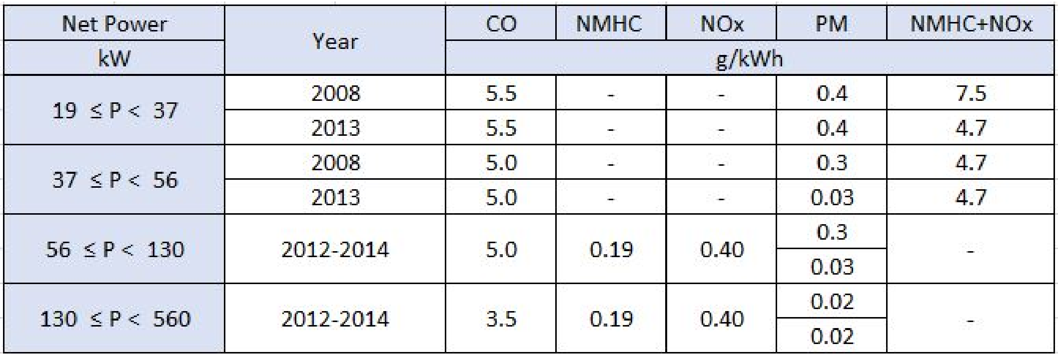
ARB and Engines makers, in 1998 US Environmental Protection Agency increased through Tier 2 and Tier 3, to be phased-in from 2000 to 2008, off-road engines emission limits for power higher than 37 kW. Moreover it introduced limits for equipments with power lower than 37 kW.
Tier 1-3 standards were complied by manufacturers by using advanced engines design, with no use or in some case limited use of exhausted gas aftertreatment, such as oxidation catalyst.



Net Power	Tier	Date	CO	HC	NOx	PM	NMHC+NOx
kW			g/kWh				
19 ≤ P < 37	Tier 1	1999	5.5	-	-	0.8	9.5
	Tier 2	2004	5.5	-	-	0.6	7.5
37 ≤ P < 75	Tier 1	1998	-	-	9.2	-	-
	Tier 2	2004	5.0	-	-	0.4	7.5
	Tier3	2008	5.0	-	-	0.4	4.7
75 ≤ P < 130	Tier 1	1997	-	-	9.2	-	-
	Tier 2	2003	5.0	-	-	0.3	6.6
	Tier 3	2007	5.0	-	-	0.3	4.0
130 ≤ P < 225	Tier 1	1996	11.4	1.3	9.2	0.54	-
	Tier 2	2003	3.5	-	-	0.2	6.6
	Tier 3	2006	3.5	-	-	0.2	4.0
225 ≤ P < 450	Tier 1	1996	11.4	1.3	9.2	0.54	-
	Tier 2	2001	3.5	-	-	0.2	6.4
	Tier 3	2006	3.5	-	-	0.2	4.0
450 ≤ P < 560	Tier 1	1996	11.4	1.3	9.2	0.54	-
	Tier 2	2002	3.5	-	-	0.2	6.4
	Tier 3	2006	3.5	-	-	0.2	4.0
P ≥ 560	Tier 1	2000	11.4	1.3	9.2	0.54	-
	Tier 2	2006	3.5	-	-	0.2	6.4

Figure 3.10: Tier 1-3 Standards

Tier 4 standard was introduced by EPA on 2004 and became effective after a phase-in period from 2008 to 2015. PM and NOx were reduced by 90 % respect the previous standard and these limits has been respected by using exhausted gases control technologies never used before.



Net Power	Year	CO	NMHC	NOx	PM	NMHC+NOx
kW		g/kWh				
19 ≤ P < 37	2008	5.5	-	-	0.4	7.5
	2013	5.5	-	-	0.4	4.7
37 ≤ P < 56	2008	5.0	-	-	0.3	4.7
	2013	5.0	-	-	0.03	4.7
56 ≤ P < 130	2012-2014	5.0	0.19	0.40	0.3	-
					0.03	
130 ≤ P < 560	2012-2014	3.5	0.19	0.40	0.02	-
					0.02	

Figure 3.11: Tier 4 Standard

3.3.1 United States Test Cycles

A steady-state test cycle, equivalent to the ISO 8178 C1 8 modes, is used to measure off-road engine emissions. Other ISO 8178 test cycles are used for specific applications, such as D2 5 modes cycle applied on constant-speed engines.

As happened in Europe with the introduction of a transient cycle that was used, in conjunction with a steady-state cycle, to test engines that would comply with Stage III/IV standard, also in U.S. Tier4 standard had to be met over both the steady-state test and the off-road transient cycle (NRTC). As in EU the NRTC includes a cold start test, with a relative weight of 5 %. The hot start weights for 95 % on the final result.

Tier4 off-road engines must also comply with "Not-to-Exceed" (NTE) standard, that evaluate emissions not following a specific cycle path but with a random test procedure. It involves speed and torque conditions af any type that could occur within the NTE controlled area, including both steady-state or transient sequences with different ambient conditions. As reported by figure 3.12 the controlled area in red contains all engine operating points within: full load torque curve, 30 % of maximum torque straight line, 30% of maximum power hyperbola, 15 % above the European Stationary Cycle (ESC) speed, 5 % of the minimum BSFC value of the engine.

The ESC speed is evaluated as: $n_{lo} + 0.15(n_{hi} - n_{lo})$, where n_{lo} and n_{hi} are the minimum and the maximum speeds at which is still available 50% and 70% of the maximum power respectively.

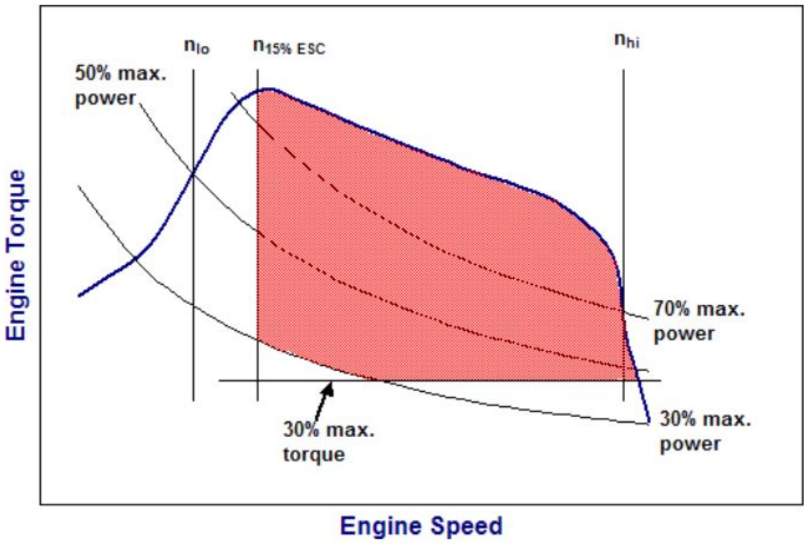


Figure 3.12: NTE zone

Generally the NTE limits are fixed to 1,25 the type approval limits, but the multiplier is increased to 1,5 if the NO_x standard and the PM standard are lower than 2,5 g/kWh and 0,07 g/kWh respectively.

3.4 International comparison

The severe reduction on the PM (that is reduced to 0.015 g/kWh from 0.025 g/kWh limit of Stage IV) and the PN limit makes the Stage V the most severe emission standard in the off-road machinery world. In order to comply with these limits it has been necessary for the engines manufacturers the adoption of diesel particulate filter. In figure 3.13 it is reported a comparison of PM and NOx limits between the EU and the U.S in terms of g/kWh.

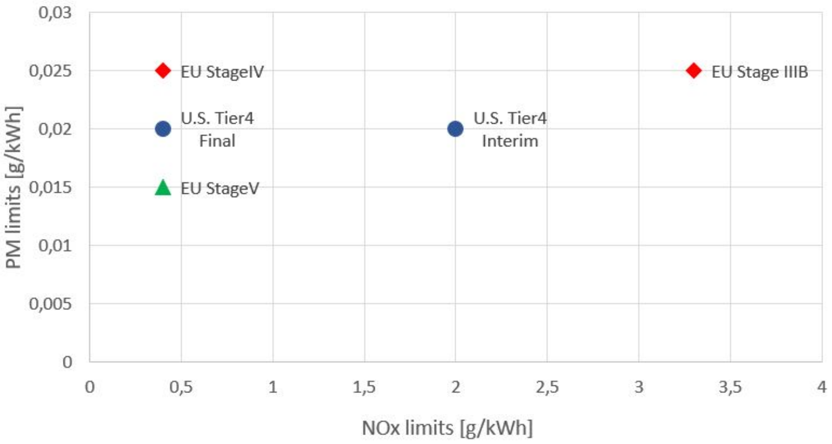


Figure 3.13: EU and U.S. Comparison

Both U.S Tier4 Interim and Tier4 Final define a lower standards in comparison with EU Stage IIIB and EU Stage IV, but they failed in the aim of forcing diesel particulate filter introduction. EU StageV on the other hand by reducing the PM limit of 25 % respect U.S. limits and introducing the PN counting took the manufacturers to the adoption of diesel particulate filter. StageV regulation sets new challenging limits that could be, in the coming years, new standards for the rest of the world.

4 DeSOx strategy refinement

4.1 Introduction

One problem faced by SCR is its sensitivity to sulfur. Sulfur compounds contained inside the fuel and lube oil oxidize to form sulfur dioxide (SO_2) and then sulfur trioxide (SO_3).The latter, in particular, poison the ion exchanged Cu sites in the zeolite structure of the SCR, decreasing the NO_x reduction capacity.

The activity that has been followed in Kohler is the fine-tuning of the sulfur regeneration (DeSOx) strategy model on a Tier4 KDI 3404 engine. This model is already defined inside the control unit software, but it has been important to refine the thresholds at which the DeSOx strategy is activated and the SOx model desorption rates, in order to reach a better alignement with experimental data and to ensure the best regeneration on the field.

Differently from Stage V KDI 3404, where in order to comply with the PM emission standards and PN counting a diesel particulate filter is adopted, on Tier4 Final engines, due to less severe PM limits (figure 3.13), the DPF system is not used. This fact is fundamental because it takes to avoid the development of a DPF regeneration strategy on the engine ECU. If this could seem to be an advantage from the calibration point of view, the DPF regeneration strategy lack takes to build and to develop a specific SOx desorption strategy in order to clean the SCR from sulfure deposits; in facts, during the usage of the engine, these deposits decrease efficiency of the Selective Catalytic Reduction catalyst (SCR).

On the Stage V KDI 3404 engine, DeSOx strategy is still present in the ECU but it's not analyzed so deeply because the SCR de-sulfuration is covered and substituded by the presence of the DPF regeneration, that performs in the meantime a DeSOx process due to the high exhaust gases temperature in the after treatement system.

From the constructive point of view, the SCR catalysts are built with ceramic material, such as titanium oxide, used for the carrier that guarantee a good resistance against thermal-shock events. On this substrate can be founded active catalytic components such as Vanadium, Molybdenum, Tungsten. Each of these presents advantages and disadvantages. For example, metals like Vanadium and Tungsten are less expensive but lack high thermal durability. They also present an high catalysing potential that takes to oxidize SO_2 into SO_3. Moreover zeolite, that form the washcoat, has the advantage to guarantee an high thermal durability.

Honeycomb and plate forms are the most common designs for SCR catalysts geometry: the first one is an exstruded ceramic applied homogeneously throughout the ceramic carrier or coated on the substrate and it presents an higher pressure drop respect the plate form with a major risk of plugging and fouling. The second one shows a lower pressure drop and it plugs less easily.

In light of these considerations, for what concern thermal durability for the Tier4 KDI 3404 SCR catalyst it has been chosen a Copper/zeolite catalyst that have high de-NO_x activity , while Vanadium it has been excluded. All these considerations has been made also for the choice of Stage V KDI 3404 SCR catalyst with deeper attention to the fact that, being present a DPF regeneration strategy, the exhausted gases temperature can be even more severe.

4.2 Chemical reactions inside SCR

For what concern the chemistry of the process, the NO_x molecules are reduced when the exhausted gases flow pass through the catalyst chamber. Before this passage, the gases are mixed with reductants such as anhydrous ammonia, aqueous ammonia or urea. Anhydrous ammonia is classified as inhalation hazard but if well managed it present the advantage of being directly used within the SCR without any further conversion. Acqueous ammonia needs to be vaporized to be used in the SCR, but it is safer to handle. Finally urea is safest to store but in order to be converted into an effective reductant, such as ammonia, it requires thermal decomposition. In (15),(16),(17) are reported secondary chemical reaction that can happen inside SCR catalyst:

$$2SO_2 + O_2 \longrightarrow 2SO_3 \tag{15}$$

$$2NH_3 + SO_3 + H_2O \longrightarrow (NH_4)_2SO_4 \tag{16}$$

$$NH_3 + SO_3 + H_2O \longrightarrow NH_4HSO_4 \tag{17}$$

Equation (15) is the most important one with reference to our fine-tuning DeSOx strategy and it takes place also inside the Diesel Oxidation Catalyst (DOC) that, from a space point of view, is installed just before the SCR (it is important to underline that, differently from StageV KDI 3404 engine, on the Tier4 solution exhausted gases after-treatment system the DPF in not used). Reaction (15) is very sensitive to thermal conditions and in the temperature window from 300 °C to 400 °C has its major effects, as can be observed in figure 4.3. This temperature window is very important because is just below the temperature levels (380 °C-400 °C) at which it is possible to assist to a thermal decomposition of sulfates on the catalyst surface, that is indicated as passive SCR regeneration process.

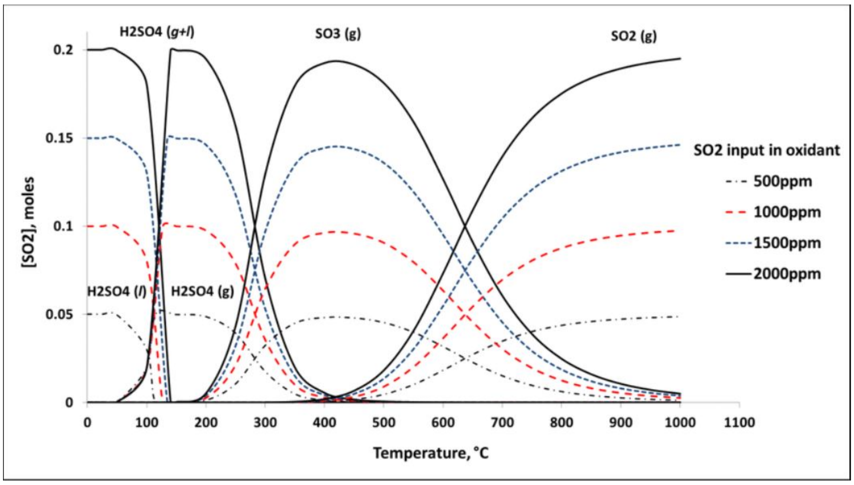


Figure 4.1: SO_3 formation

Our analysis has been extremely focused on SO_3 formation because it is known that it is responsable for Cu/zeolite SCR sulfur poisoning. The formation of SO_2 does not generate a comparable order of magnitude poisoning level respect to SO_3 and so its effects is not taken into account in our test.
The poisoning phenomena greatly reduces overall SCR performances and it is an issue to study as long as sulfur remains within fuel and engine oil, even if a low sulfur fuel is used. During SCR poisoning, sulfur compounds adsorbs on the ion-exchanged Cu sites in the zeolite structure. Due to the fact that are just the Cu sites (figure 4.2) within the zeolite structure that are responsable for the catalytic activity, blocking these sites causes the mentioned decrease of SCR performances.

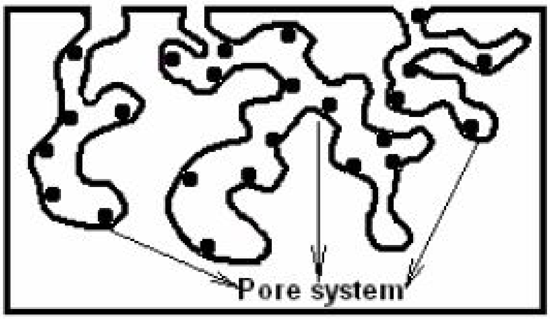


Figure 4.2: Poisoning mechanism

With regards to sulfur tolerance, in order to certify Tier 1-3 engines it was used fuel with sulfur level no greater than 0.2 wt% (2000 ppm), while with Tier4 standard, from 2011, engines are tested with fuels that present a sulfur content fuel between 7 and 15 ppm.
In order to recover the SCR performance, the catalysts can be regenerated by decomposing the sulfur compounds. This process is identified as DeSOx, at high temperatures in lean conditions.

4.3 Tests performed

In order to present the tests that have been done to validate the fine-tuning of the DeSOx strategy, it is important to give a short account about the model that works inside the engine ECU and control the regeneration strategy. The model presents as input parameters 3 main variables:

- Temperature of exhaust gases at the SCR inlet
- Exhaust gases mass flow rate
- Estimated of sulfur emissions from the engine

The last imput parameter is not a measured data, but it derives only from a ECU map. By knowing these values, the model is able to elaborate two specific quantities: an accumulation term and a release term. The algebraic sum of these two quantities indicates if the system is releasing or it is storing sulfur. The goal of the fine-tuning activity is to properly set the releasing term in a certain range of SCR inlet temperatures so to validate the DeSOx activity in a extended temperature range respect the previous model.
The validation process consists in five steps, each one is performed as a test cycle on the previously mentioned Tier4 KDI 3404 engine. Every test cycle is performed on the dyno-brake and the data are acquired using MDA-INCA software, that allowed to collect engine and after treatment parameters, such as temperature and pressure with a saving interval time setted by the user. The main parameters that have been taken as reference for our validation process are:

- η_{NO_x}
- Δ_{NO_x}
- T_{SCR}

The first one is the SCR catalyst efficiency defined as:

$$\eta_{NO_x} = \frac{NO_{x,IN} - NO_{x,OUT}}{NO_{x,IN}} \tag{18}$$

where NO_x quantities are measured in ppm. The second one is the Δ_{NO_x} parameter, defined as:

$$\Delta_{NO_x} = NO_{x,OUT_{Measured}} - NO_{x,OUT_{Model}} \tag{19}$$

Both these quantities are measured in ppm. In general, Δ_{NO_x} parameter is negative in order to keep the system in a overperforming status through a conservative calibration, in other words a conservative model. It will be observed that in a SCR poisoned with SO_3 this parameter will be positive due to underperforming conditions.
Finally the third parameter is the key one because it indicated the SCR exhausted gas temperature and it is fundamental because it controls the beginning of the regeneration strategies and it is the proof that every cycle has been performed at the same temperature levels.
As we mentioned before the validation process consists of five engine cycles (or steps) to be performed in sequence (Figure 4.3).

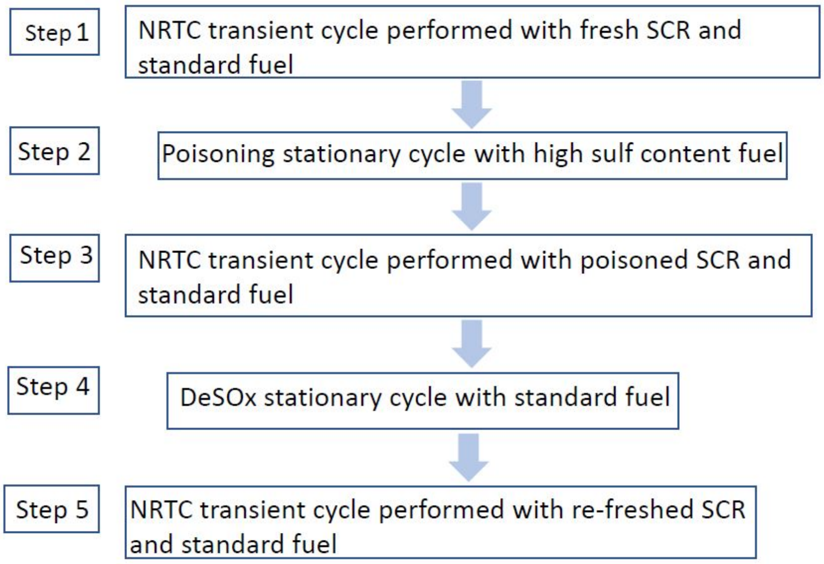


Figure 4.3: Followed steps

4.3.1 Step 1

In the first step the NRTC cycle is performed with a fresh SCR that guarantee the standard performances in terms of NO_x reduction. The fuel used is standard with low sulfur levels. It has been chosen as reference cycle, to compare SCR performances in different conditions, the NRTC transient cycle due to the fact that it is a cycle used by the authority to test emissions levels and for SCR temperature levels obtained, because the target was to have temperatures at the SCR inlet lower than 350 °C. NRTC cycle provides this result, as can be observed in figure 4.4.

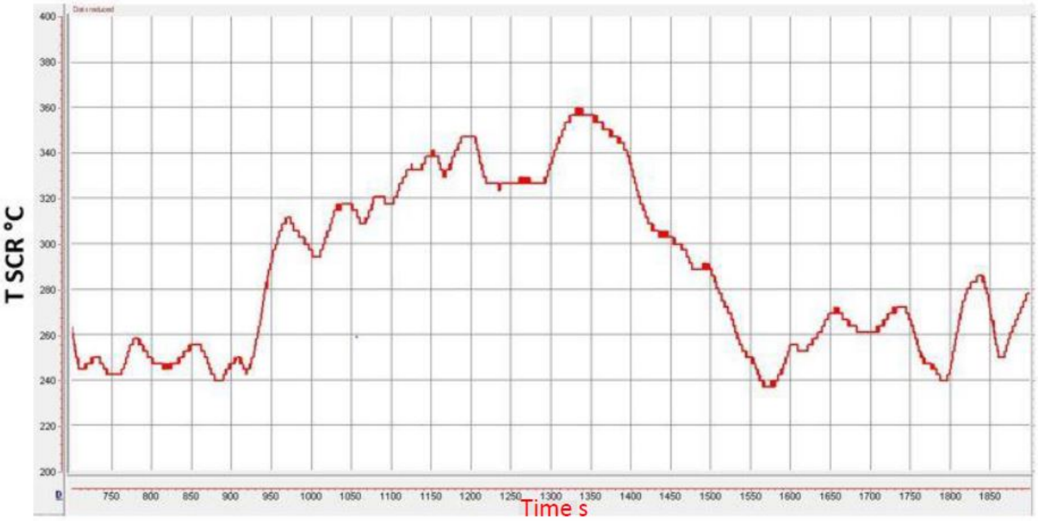


Figure 4.4: SCR inlet temperature

NRSC can not be used for this reference cycle because SCR inlet temperature would be higher than 380 °C. This represents a problem because doing a reference cycle (it will be shown that this is referred to step 3 of figure 4.3) with a SCR inlet temperature so high can generate passive SCR regeneration in a step of the validation procedure where we would only measure SCR performances and our target is not SCR regeneration.

4.3.2 Step 2

Step 2 , as can be seen in figure 4.3, consists of a poisoning phase: a stationary cycle in a defined engine operating point is performed.
Both the cycle duration and the specific functioning conditions of the engine derives from some considerations:

1. for what concern poisoning stationary cycle duration it has been used an interval of 4 hours. It is important to underline that during this phase a fuel with an high sulfur content (200 ppm) has been adopted in order to accelerate the poisoning phase, reducing the time request for this activity. But during the "on-field" usage of the engine a so high sulfur level fuel is not accepted, at least on the U.S. market where the Tier4 KDI 3404 engine is sold and the maximum sulfur level is imposed to 15 ppm.

2. regarding engine functioning condition it has been adopted an operating point of 1600 rpm with 40 % load. This choice has been dictate, once again, by the SCR inlet temperatures.

From the ECU point of view, the poisoning phase is considered as a sulfur accumulation inside the SCR catalyst up to a certain threshold, but the sulfur level is not measured. This means that the ECU works with a map that assumes the SCR sulfur content. In our validation loop the sulfur threshold for DeSOx strategy activation is manually set to 4,5 g due to the fact that we are using an high sufur content fuel. In the final model ECU will evaluate sulfur accumulation, until sulfur threshold is reached, using fuel consumption and temperatures data, considering a standard fuel with maximum 15 ppm. It is extremely important to underline that a real content of sulfur inside the SCR is not easily measurable; this is only a reference that has been assumed for model calibration and it is used for control unit run. The only solid proof to be presented to agencies is the NRTC emissions check after a DeSOx event, that should be comparable to NO_x levels before the poisoning step. On the contrary, a poisoning level evaluated through chemical computation would be resulted less solid and too much dependent from external parameters.
In the following passages it will be showed how it has been possible to validate this poisoning threshold.

4.3.3 Step 3

Once the poisoning step is concluded another NRTC transient cycle is performed. Now the transient cycle has the purpose to analize how the SCR catalyst efficiency is decreased.
Also the Δ_{NO_x} parameter shows an interesting behaviour: as previously anticipated its value becames positive to represent an underperforming condition. As a check it is necessary to evaluate that this NRTC ,with poisoned SCR, is performed at the same SCR temperature of the first NRTC with fresh SCR.

4.3.4 Step 4

In the fourth step the DeSOx procedure is conducted manually. Starting from the poisoning level previously fixed at 4,5 g, the engine runs at a specific operating point, that guarantee an arbitrary SCR inlet temperature, until a 0,3 g SCR sulfur level is estimated by the control unit considering SCR functioning conditions. The validation procedure has been performed several times in order to validate different DeSOx temperatures, in particular the temperatures tested has been: 380 °C, 400 °C, 420 °C, 450 °C, 500 °C.

4.3.5 Step 5

The fifth step consists of the final NRTC transient cycle that is performed to check if after the DeSOx procedure the SCR system regains its fresh efficiency. If the DeSOx procedure has completely cleaned the SCR from sulfur contamination also the Δ_{NO_x} parameter recovers its negative value.

It has been said before that the SCR poisoning level has to be validate, now it is possible to show how this result can be obtained. It is known that the poisoning threshold has been chosen arbitrary, in fact what is really important and fundamental is the temperature and a regeneration time period that it is necessary to evaluate, called ”t”. If we have a certain logic regeneration interval, ”t'”, given by the time difference between the control unit estimated sulfur levels of 4,5 g and 0,3 g during the DeSOx procedure, the one at 450 °C SCR temperature level is of 17 minutes. Through the parameters analized it is possible to observe that both the SCR efficiency (η_{NO_x}) and the Δ_{NO_x} parameter regain newly a value higher that $\eta_{NO_{x,Ideal}}$ and a negative value respectively, before the logic regeneration time interval t'. This is the proof that we have a certain safety margin represented by the difference between t' and t and that 4,5 g poisoning level is sufficient, from the ECU point of view, to completely regenerate the SCR catalyst.

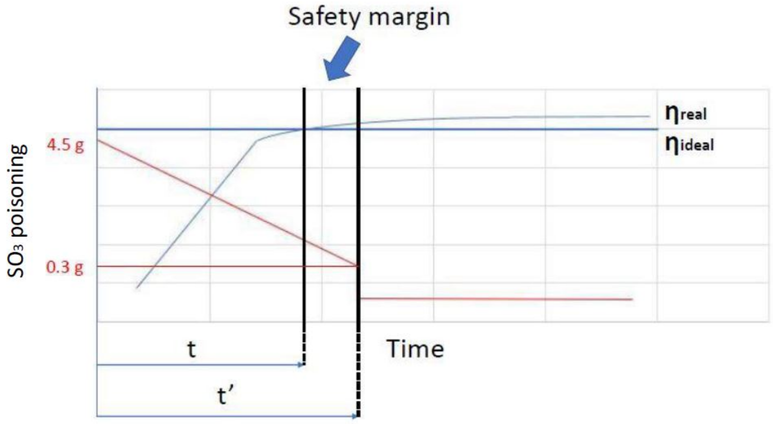


Figure 4.5: Conceptual graph

These results illustrate that our model is conservative because, as it will be shown in the 4.4 section, the difference t'-t will be always positive and this means that we have obtained a certain safety margin at all DeSOx temperatures levels, at which we have fine-tuned the model.

4.4 Results obtained

It is possible to report the results obtained at all DeSOx temperatures levels (380 °C, 400 °C, 420 °C, 450 °C, 500 °C) at which the validation loop has been performed.

The comparison between NRTC transient cycle is presented in figure 4.6, in terms of parameters that has been taken as reference, it is possible to observe, for what concern η_{NO_x}, a decrease after the poisoning phase (blue line) and a good recovery to initial efficiency levels during the Step 5 NRTC transient cycle after the DeSOx phase (green line). This means that the DeSOx phase has the intended effect and it is not observed any efficiency non recovery.

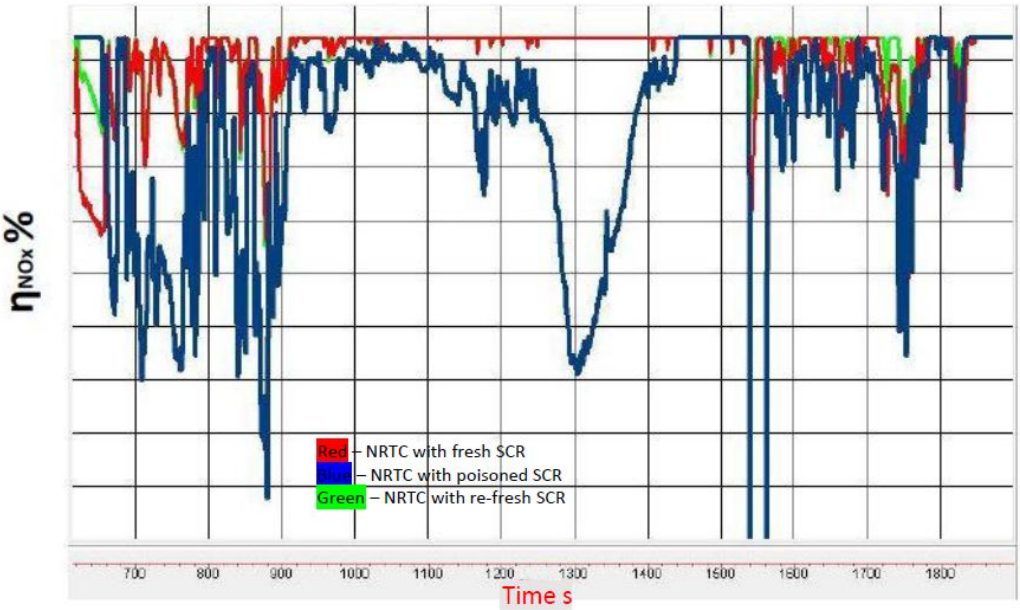


Figure 4.6: η_{NOx} NRTC-transient cycles comparison

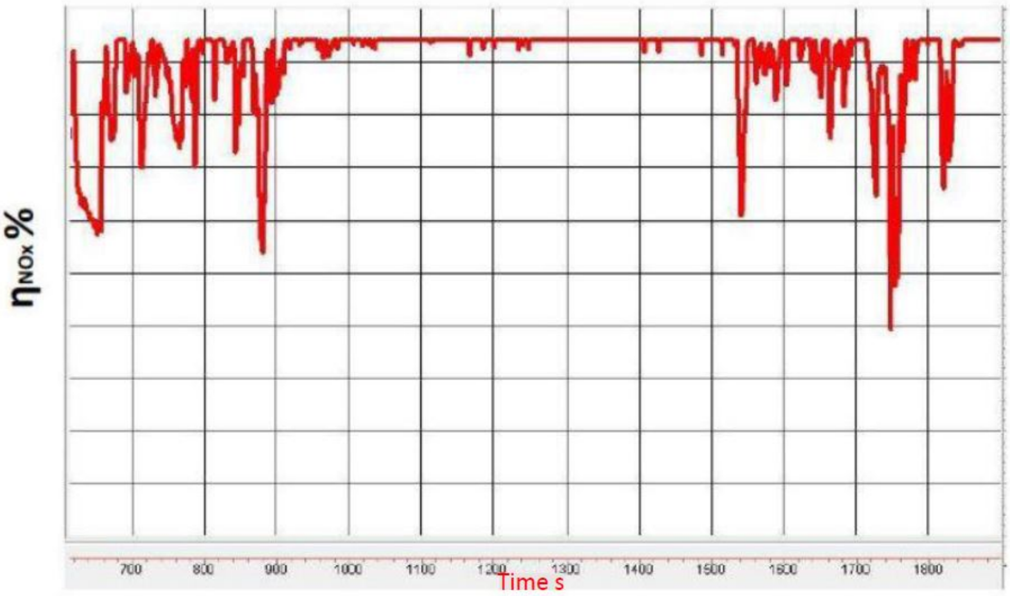


Figure 4.7: η_{NOx} NRTC-transient cycle fresh SCR

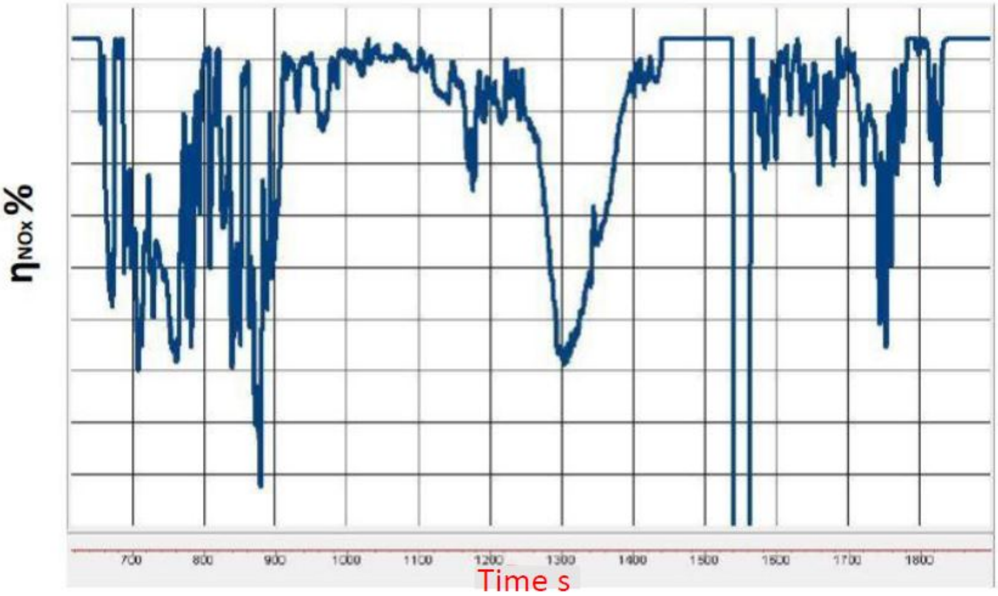


Figure 4.8: η_{NOx} NRTC-transient cycle poisoned SCR

Figure 4.9: η_{NOx} NRTC-transient cycle re-fresh SCR

The same comparison can be performed looking at Δ_{NO_x} parameter (figure 4.10), that assumes a general negative value over the NRTC transient cycle with fresh SCR. Over NRTC cycle after the poisoning phase, Δ_{NO_x} parameter takes a positive value and this is caused by the underperforming behaviour: the value of the $NO_{x,OUT_{Measured}}$ at the SCR outlet is higher than $NO_{x,OUT_{Model}}$ estimated by the model, due to sulfur poisoning. In the NRTC transient cycle runned with re-fresh SCR, Δ_{NO_x} parameter regains its negative values, similar or even equal to NRTC values of step 1 in almost all points of the cycle.

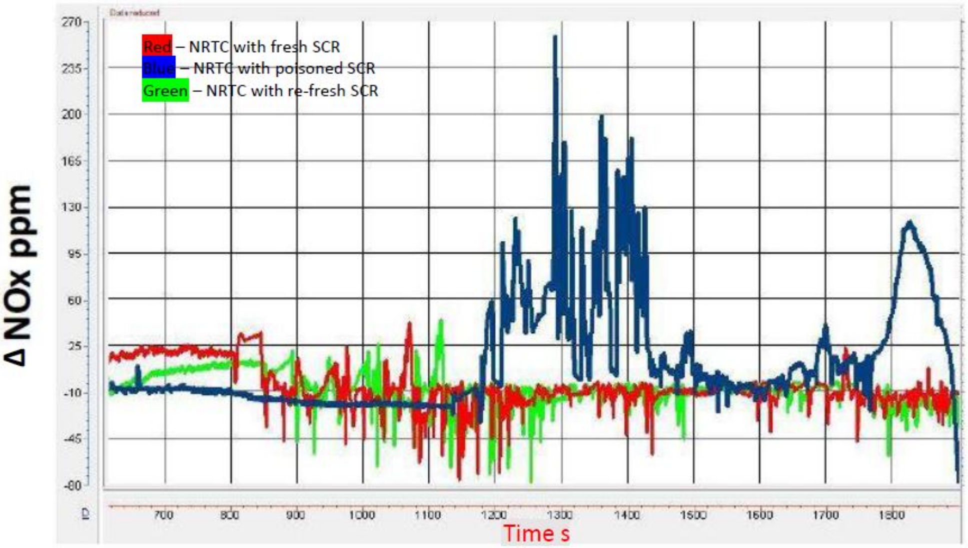


Figure 4.10: Δ_{NO_x} NRTC-transient cycles comparison

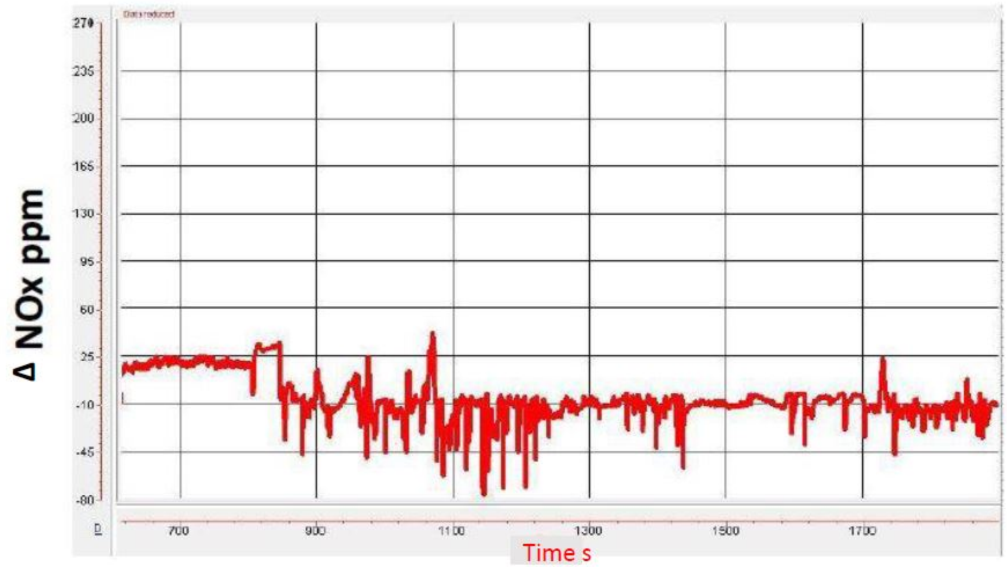


Figure 4.11: Δ_{NO_x} NRTC-transient cycle fresh SCR

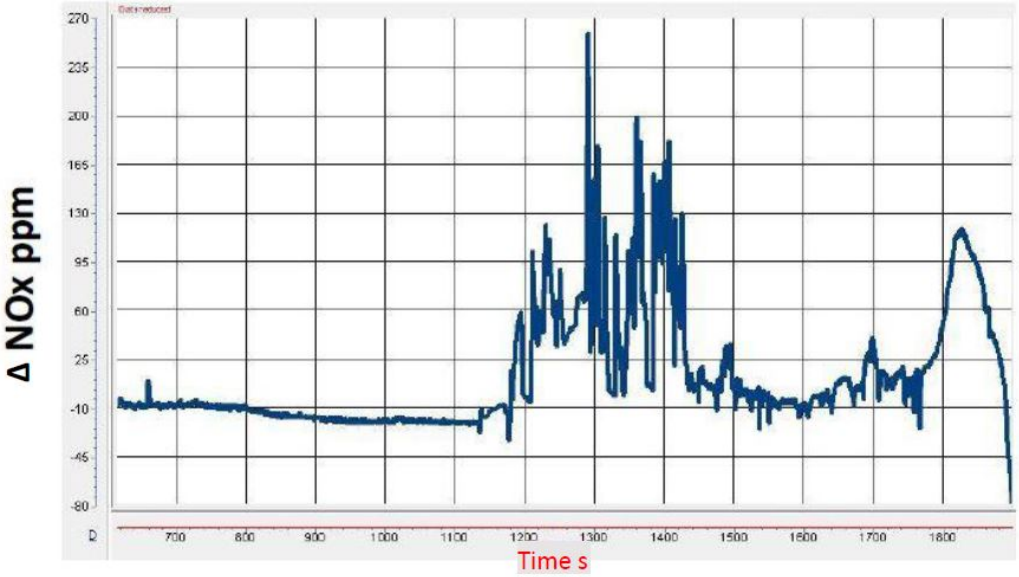


Figure 4.12: Δ_{NO_x} ppm NRTC-transient cycle poisoned SCR

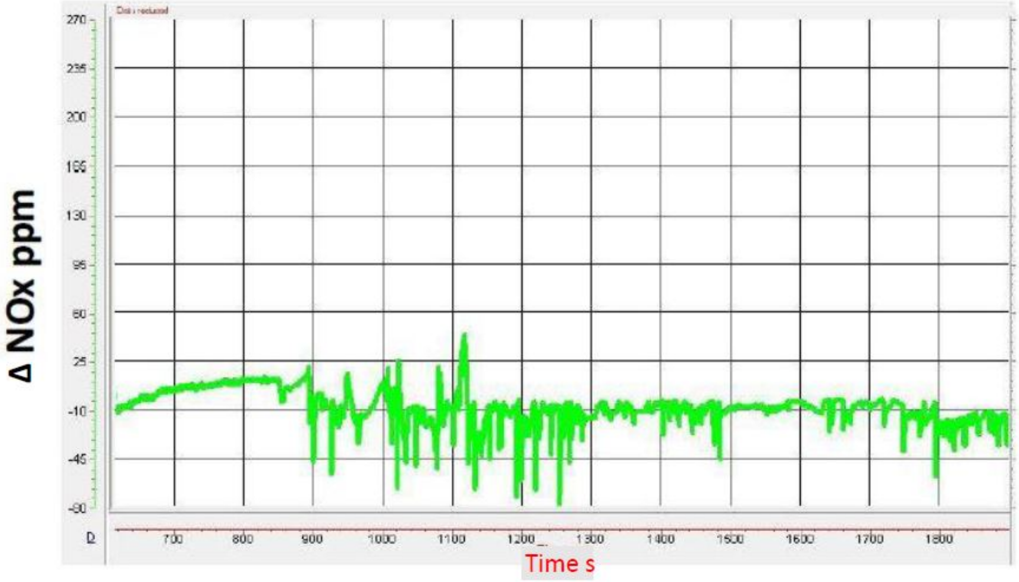


Figure 4.13: Δ_{NO_x} NRTC-transient cycle re-fresh SCR

In the validation procedure and comparison between NRTC transient cycles it is important to show also the SCR temperatures in order to demonstrate that the analysis has been performed with the same boundary conditions. In figure 4.14 has been reported the path of the SCR temperatures over the NRTC transient cycles performed.

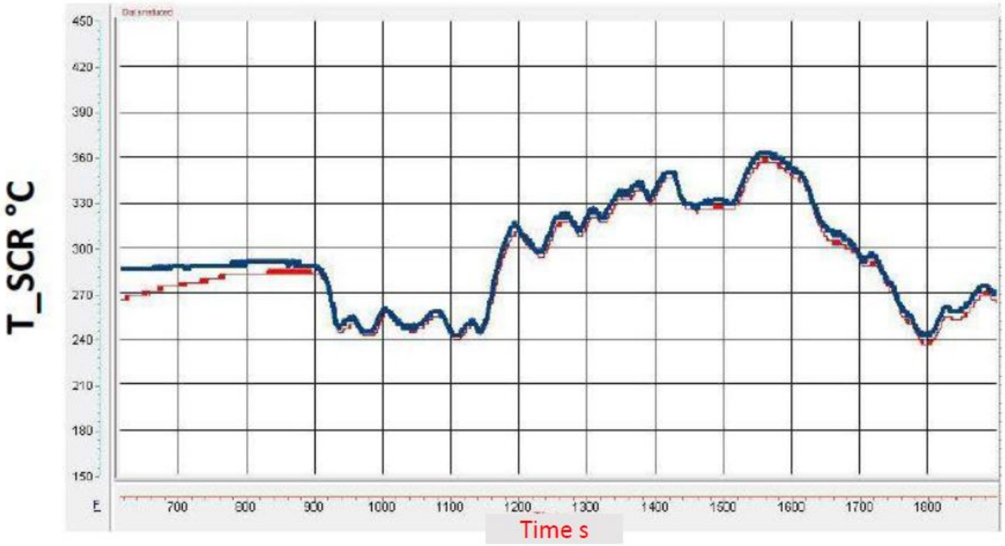


Figure 4.14: SCR Temperatures

It is important to say that this NRTC transient cycles comparison has been performed for every different DeSOx temperature level at which this model is validated: what it has been just compared derives from the DeSOx validation process at 450 °C. It will be shown also the NRTC comparison for others DeSOx temperature levels validation loops.
For what concern the poisoning phase in figure 4.15 has been plotted the η_{NO_x} parameter. It has a decreasing pattern deriving from the poisoning activity performed during this phase.

Figure 4.15: η_{NO_x} during poisoning phase

The Δ_{NO_x} parameter shows the characteristic behaviour that has already been analized for the NRTC transient cycle: over the course of the poisoning phase its value passes from negative to positive, as can be observed in figure 4.16.

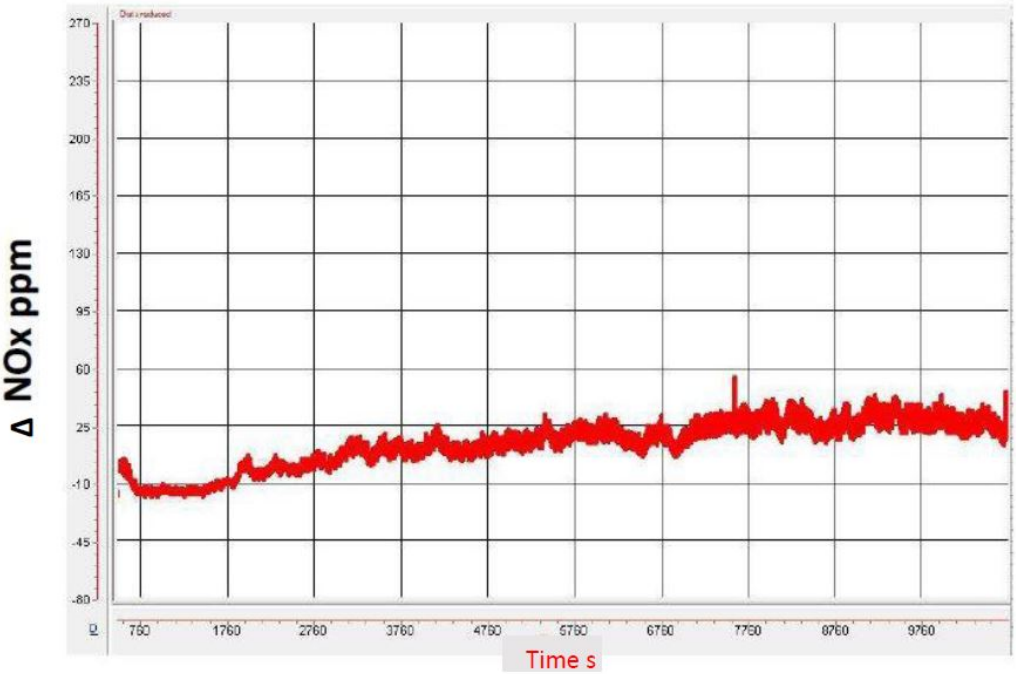


Figure 4.16: Δ_{NO_x} parameter during poisoning phase

As it has been said before for the NRTC comparison, also this poisoning phase derives from a specific DeSOx temperature level validation, in particular it belongs to 450 °C DeSOx loop.
Finally, in figure 4.17, is reported the SCR inlet temperature during this poisoning phase

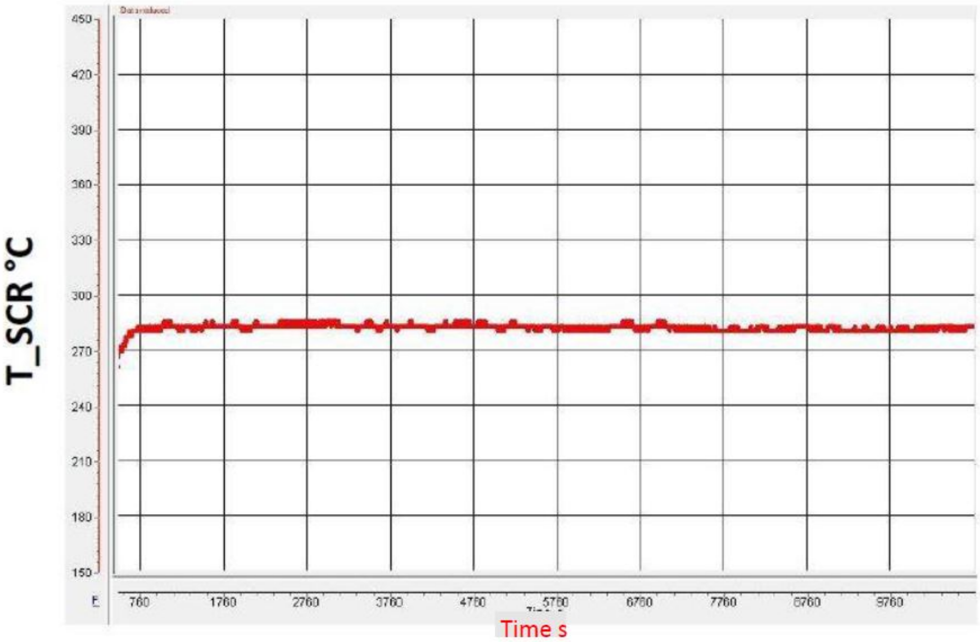


Figure 4.17: T_{SCR} °C during poisoning phase

At 450 °C (figure 4.18) it is possible to illustrate the results obtained from the DeSOx phase.

Figure 4.18: T_{SCR} °C during DeSOx phase

In figure 4.19 it has been presented the NO_x efficiency recovery obtained during the DeSOx phase (the spike has no physical meaning and derives from a reset in the NO_x sensor).

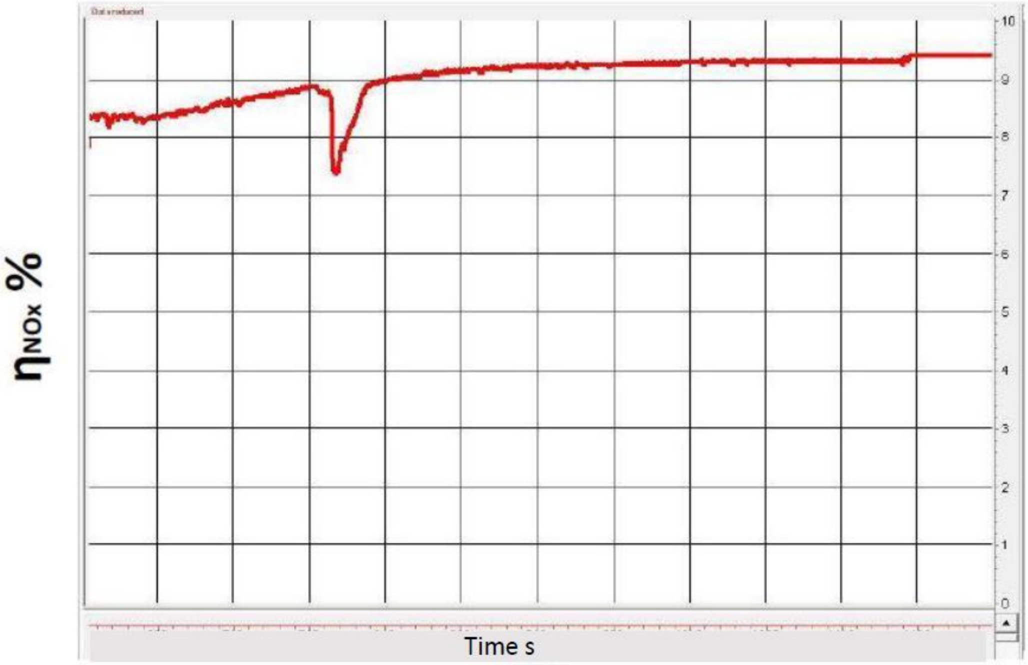


Figure 4.19: η_{NO_x} during DeSOx phase

Accordingly to the NO_x efficiency recovery, in figure 4.20 is reported the Δ_{NO_x} parameter shifts to negative values.

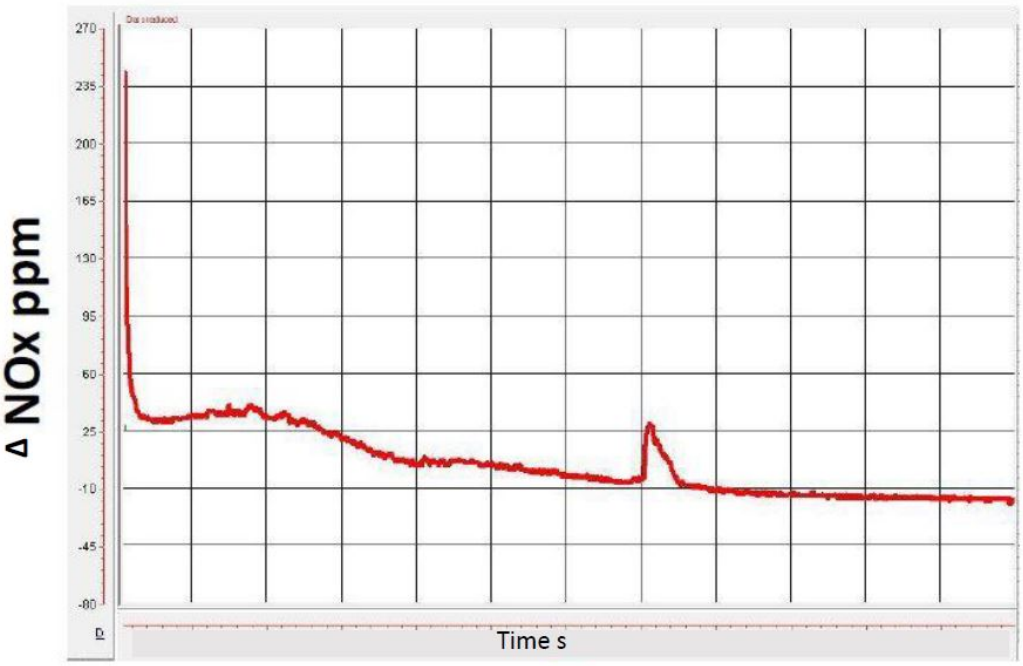


Figure 4.20: Δ_{NO_x} parameter during DeSOx phase

Eventually what is crucial in order to validate our model is to show that, although the logic regeneration period has a certain temporal duration $t^{'}$ (given by the time between the control unit estimated sulfur levels of 4,5 g and 0,3 g) , the ideal target $\eta_{NO_{x,Ideal}}$ has been reached after a time interval t lower than $t^{'}$ (figure 4.21). This allows to obtain what before (figure 4.5) has been called positive safety margin (defined as $t^{'}$-t).

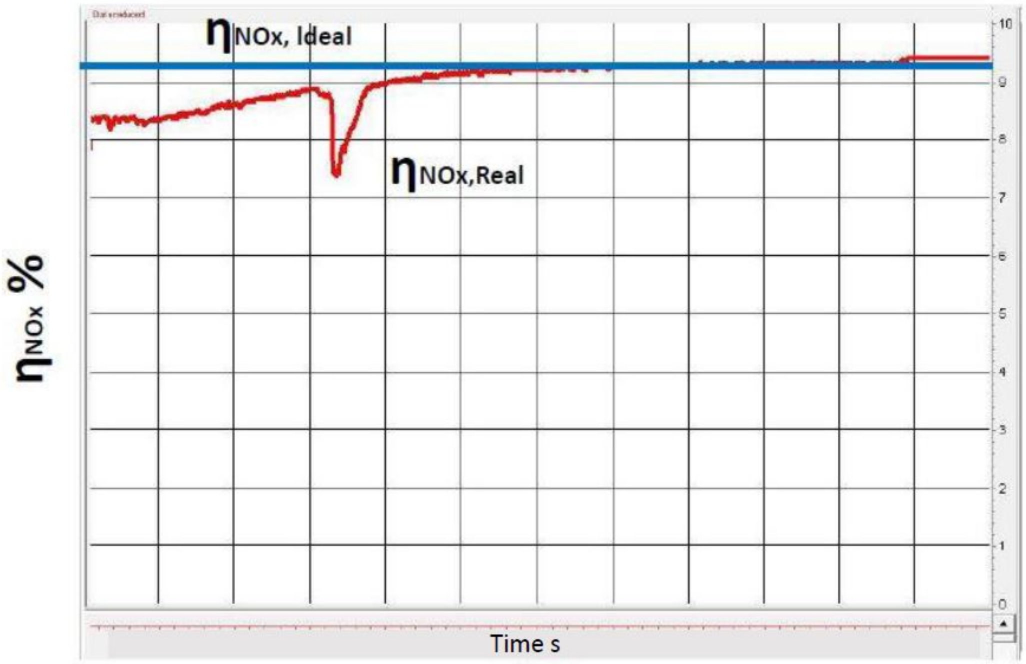


Figure 4.21: $\eta_{NO_x,Real}$ and $\eta_{NO_x,Ideal}$ during the DeSOx phase

The same validation can be performed at all others DeSOx temperature levels. The results are reported in figure 4.22 where it is presented the comparison between the DeSOx duration of the fine-tuned model and the real NO_x efficiency recovery. As it can be noticed the safety margin is always positive.

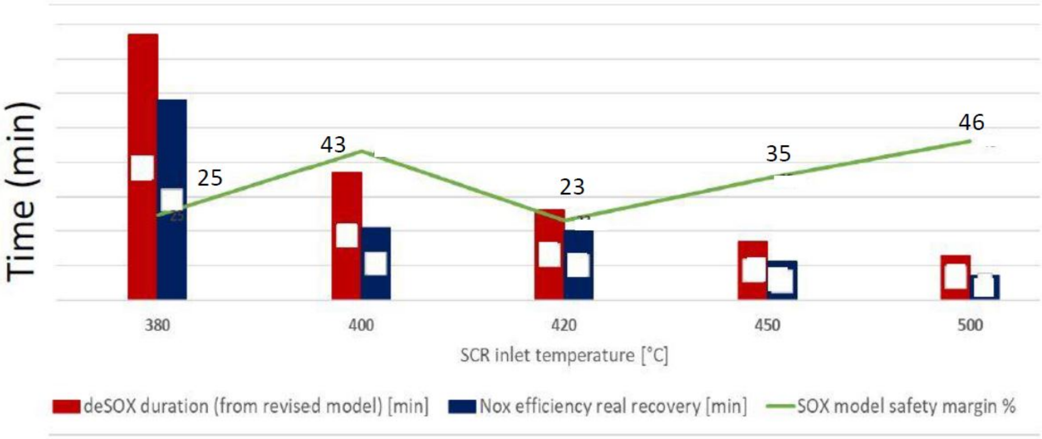


Figure 4.22: DeSOx times comparison

By fixing the $\eta_{NO_{x,Ideal}}$ target and the temperature level the only variable that change is the regeneration time. The final result is a is a trade off between time and temperature, because high temperature are challenging to obtain with ECU strategies and the drawback is the increase of HC production.

4.4.1 NRTC validation loops

In this section has been reported the NRTC-transient cycles comparison for the validation loops at 380 °C. It has been proved that η_{NO_x} completely recover after each DeSOx procedure and as a consequence the Δ_{NO_x} parameter regains its negative value. Eventually it is plotted the SCR inlet temperature in order to show the boundary working conditions.

380 °C loop

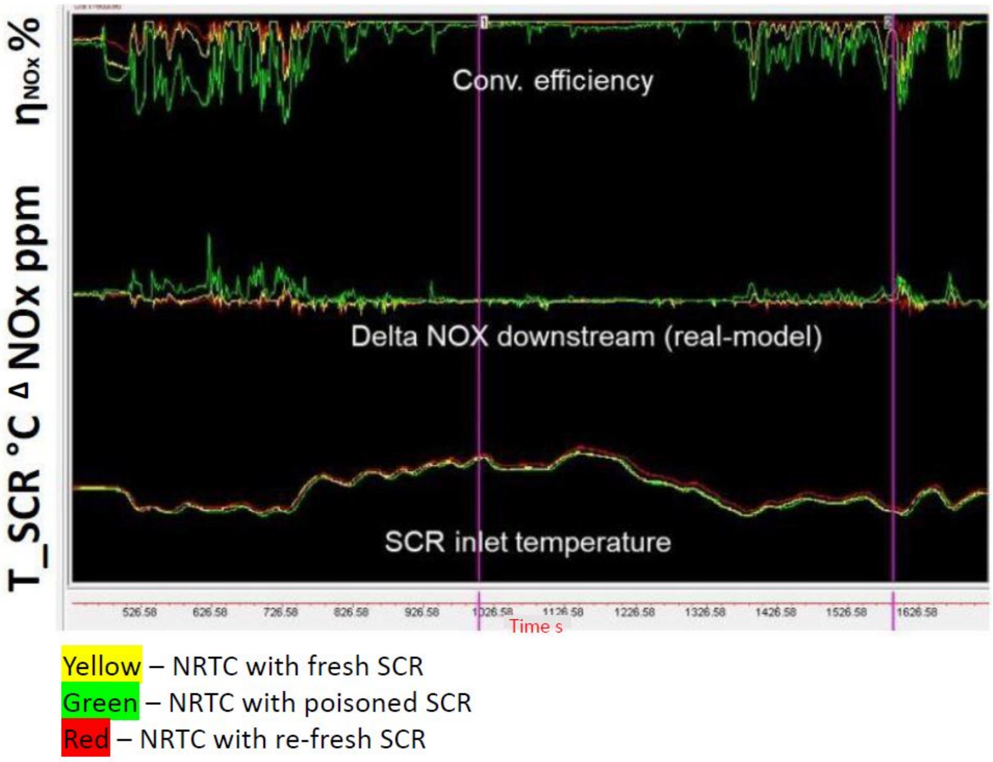


Figure 4.23: 380 °C NRTC cycles comparison

400 °C loop

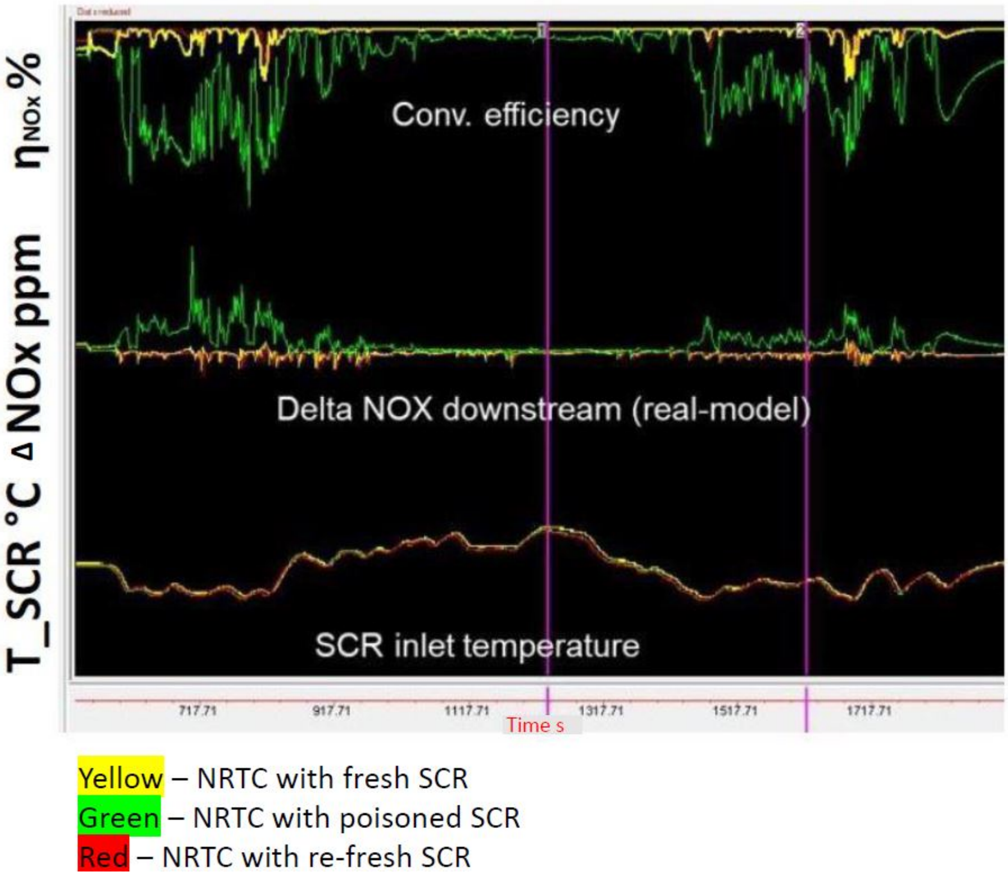


Figure 4.24: 400 °C NRTC cycles comparison

420 °C loop

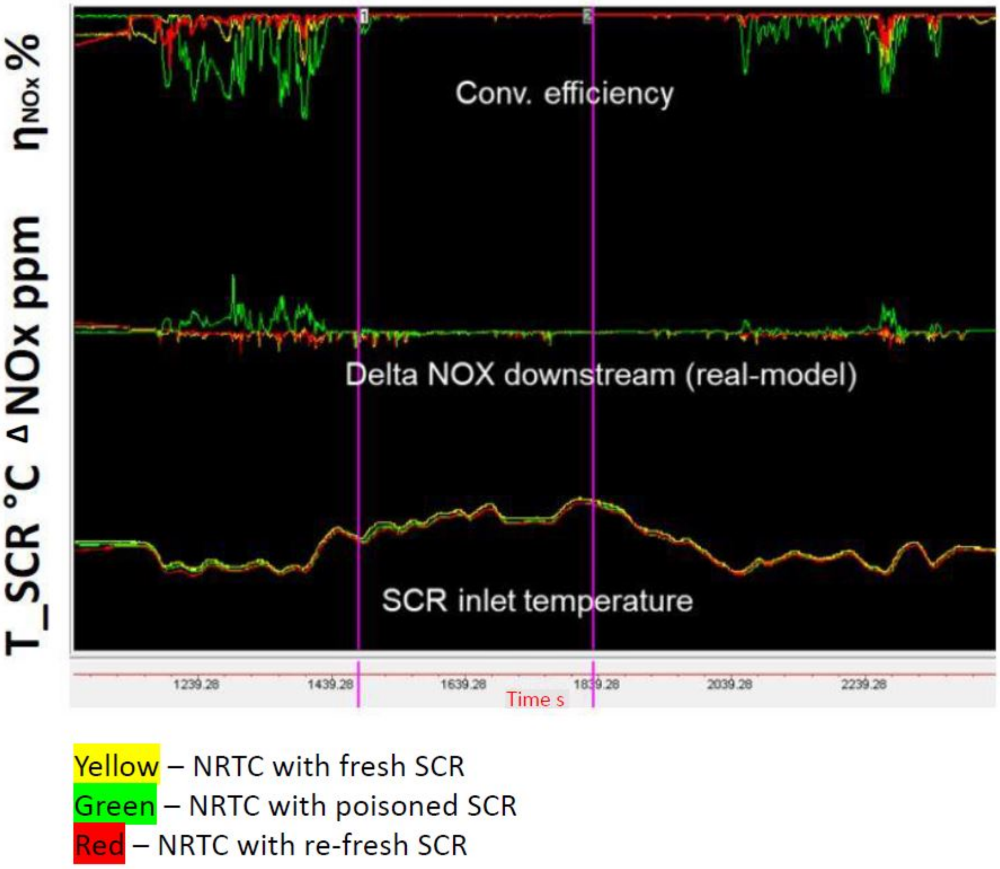
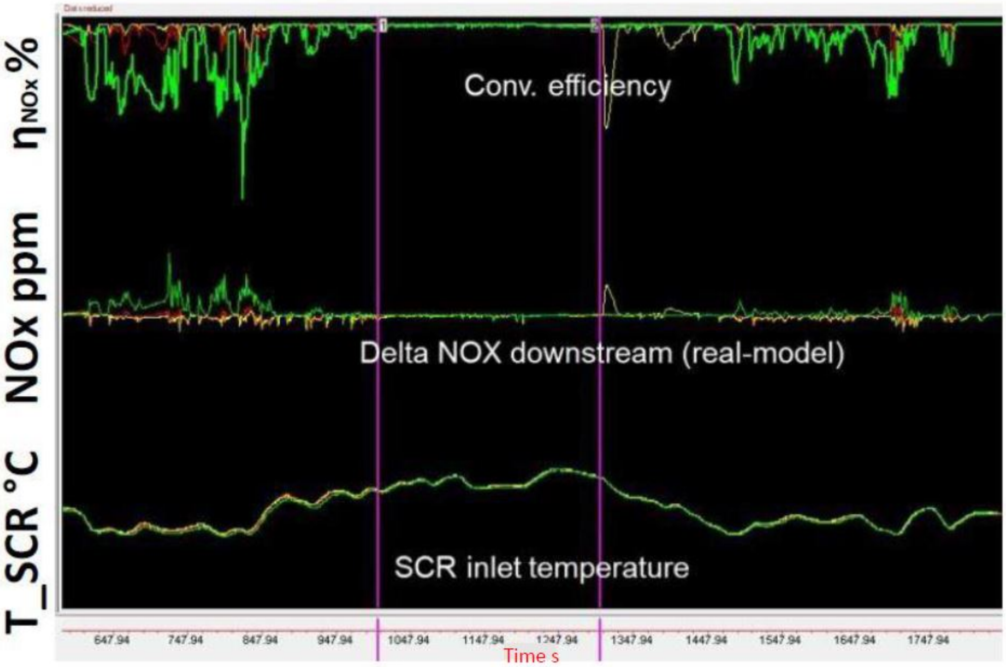


Figure 4.25: 420 °C NRTC cycles comparison

500 °C loop



Yellow – NRTC with fresh SCR
Green – NRTC with poisoned SCR
Red – NRTC with re-fresh SCR

Figure 4.26: 500 °C NRTC cycles comparison

5 Soot accumulation tests

5.1 Introduction

The introduction of DOC plus DPF solution on KDI 3404 Stage V engine has generated the necessity of knowing and studying how these two systems works together and in particular to understand the soot accumulation behaviour on the DPF filter. In order to do this activity the KDI 3404 engine worked on the dyno-brake performing a lot of operating cycles, that have different purposes. General cycles as NRTC has been used in order to understand soot accumulation behaviour on a cycle that reaches all possible speed ranges and working loads and it is used to test Stage V emission limits. Other cycles, such as low load cycle, has been tested in order to investigate the DPF filter behaviour in critical conditions, from the smokiness and low exhausted temperature point of view. Then also an effective ”on-field” machine cycle has been performed, not directly used to weight the soot accumulated, but instead to check if the exhausted temperature levels on the low load cycle, simulated at the dyno-brake, were correct. This has been done because it was the first time that in Kohler was conducted a soot accumulation procedure on a KDI 3404 Stage V engine, equipped with a DPF constructive solution different respect the DPF mounted on KDI 2504 and 1903 , and the experience about low load cycle was preliminary.

5.1.1 Activity purpose

For what concern soot accumulation tests, performed during the emission standard development of a specific engine in an ”endurance” engine cell, it is possible to identify four phases: the phase here reported belongs to the first one. Performing the previously mentioned cycles, mainly NRTC and low load cycle, that as it has been said before are the more representative and critical, the main purpose is to search the so called balance point or in absence of this one the threshold to completely clog the filte. With the concept of balance point is defined a threshold from which the soot accumulated, expressed in grams per liter of filter volume, on the DPF doesn't change significantly considering a certain error margin due to weighting procedure.
With a low load cycle the balance point condition has not expected to be found or in general this value is very high, since the exhaust gas temperature, being under 400 °C, doesn't allow to passively regenerate the filter and as a consequence the DPF filter accumulates only.
It is important to clarify what is indicated with DPF filter regeneration. Basically thermal regeneration of the filter, from solid particles to gaseous products, is performed and two groups of filter regeneration strategies exist:

- Assisted regeneration
- Natural regeneration

With the concept of assisted regeneration is indicated the use of a specific engine calibration strategy that has the target of obtaining higher exhaust gases temperature. This purpose is reached by using the DOC as a real catalytic burner that utilizes as fuel after and post injections, in order to promote controlled oxidation processes, that occur via reaction with oxygen, on the DPF filter.
On the contrary natural regeneration can be further subdivided into active and passive one. Active regeneration allows soot natural oxidation on the filter and takes place with exhausted gases temperature higher than 300 °C - 450 °C. If temperature is lower a passive regeneration is identified: nitrogen dioxide based regeneration is conducted. The NO_2 availability is increased through the catalytic oxidation of NO by the DOC .
On a low load cycle the probability to reach the balance point is not so high, because due to temperature levels the natural regeneration has a minimum effect and the soot particles are continuously accumulated on the filter. Anyway the result is positive if it is employed a long time interval to reach the maximum threshold of soot accumulated: this means that the engine mounted on the vehicle can work a lot of hours before the assisted regeneration strategy starts. On the other hand on the NRTC, due to higher loads, balance point is expected to be reached.
Furthermore in the first phase it is convenient to perform a soot accumulation test by using as cycle the NRTC but in this case with a de-rated calibration, in particular with a maximum power of 75 kW. This test is useful to verify that the balance point has two limits: one limit given by full power calibration, while the other setted by de-rated calibration. It will be possible to verify that the balance point that can be reached with this calibration has a higher value (this point couldn't also be reached) due to the fact that with a power calibration decrease the NRTC cycle looks like a low load cycle.
The second phase, belonging to soot accumulation tests, involves a lot of different cycles: not only NRTC cycle, that is repeated, but also customers cycles. The difference consists in the fact that the calibration is completely characterized at the emission bench and it has been created a ECU model that estimate the soot production, by taking as input engine operating points. This phase is extremely important because it is possible to analize and compare the results from the DPF weighting procedure and from the ECU model: if the results are different it is possible to fix the model. The weighting procedure should be as precise as possible.
The third phase involves the validation of the model that is performed both in nominal and in critical environment conditions. It is important to have a model that slightly overstimate always the soot accumulated.
The fourth phase is the so called ”robustness”, the ECU model is applied to an engine that for the conjunction of engine component and tolerances has a smokiness greater than that of a standard engine. In this last phase it is important to analize if the model is able to adapt or its behaviour diverges.

5.2 Experimental procedure adopted

The main purpose of this section is to describe the main steps that are followed in Kohler in order to measure the soot accumulated on the DPF filter with a specific cycle. This procedure is very general and can be applied in each of the stages that have been reported in 5.1.1 . The steps are:

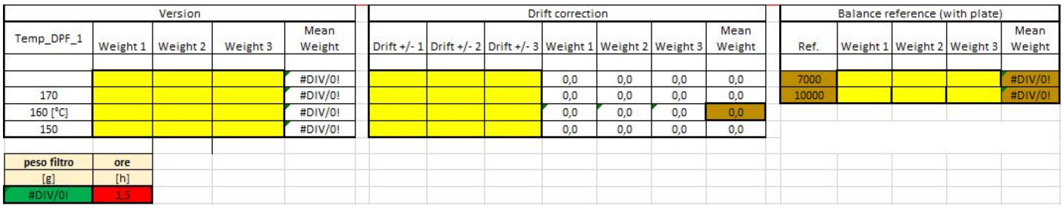
1. Degreening and zero weight
2. Accumulation phase
3. Stabilization phase
4. Weighting phase
5. Regeneration phase

Points 1,2 and 5 are performed in a specific endurance cell where the engine follows, repeating several times, the same cycle. It can work also at a fixed speed and with a certain percentage of gas pedal in order to execute point 5. The degreening phase is done by following a specific cycle, similar to NRTC, but it is executed only if the DPF is fresh without ash accumulation .
The endurance cell simulates the on-field functioning of the engine for a certain amount of hours. It is controlled by a specific bench software, called AdaMo, that impose the functioning speed and, through the use of a magnetic brake, the braking-torque to the engine. By using thermocouples sensors and pressure trasducers the same software is able to read temperatures and pressure levels in strategical point of the engine, such us oil pressure and temperature and exhaust gases temperatures at the outlet of every cylinder, just after the exhaust valves. Moreover, by using a different software called INCA, it is possible to read also other parameters coming from the engine, in particular to analize all the parameters that are collected in the electronic control unit (ECU) and in the dosing control unit (DCU), that controls the milligrams per second of urea injected inside the SCR. The connection between this software and the ECU and DCU is realized by using the CAN communication protocol.
The other phases takes place in other places: the zero weight and the weighting procedure are performed in a separated room where a micro-precision scale is present.
The stabilization phase, that is done in order to promote the evaporation of the hydrocarbons deposited on the soot particles and to eliminate the moisture present inside the filter, can be realized in two different ways:

a. bench stabilization
b. oven stabilization

In order to realize the bench stabilization the DPF is not disassembled from the after treatment system, but this process is realized by using the exhausted gases system produced by the engine that works for a certain period of time ,

comprised between 5 and 10 minutes, in specific operating conditions characterized by DPF inlet temperatures not higher than 280 °C. If the temperature exceeds this threshold a passive regeneration can start, falsifying the following weighting phase of the DPF.
With the b. type of stabilization the DPF is dismounted from the after treatment system and is putted for approximately 30 minutes inside the oven at 300 °C. This time interval has been assumed sufficient in order to realize a complete evaporation of HC deposited on the soot particles.
During the weighting phase a scale with a precision of 0.1 g is used in order to evaluate the soot accumulated on the filter. The weight of the DPF is performed 3 times, each time at a decreased temperature level: 170 °C, 160 °C, 150 °C and a drift evaluation is connected with every measure. Each data is reported in a table similar to figure 5.1. Furthermore a measure of the standard weights is done to correct the scale error.



Version				
Temp_DPF_1	Weight 1	Weight 2	Weight 3	Mean Weight
				#DIV/0!
170				#DIV/0!
160 [°C]				#DIV/0!
150				#DIV/0!

Drift correction						
Drift +/- 1	Drift +/- 2	Drift +/- 3	Weight 1	Weight 2	Weight 3	Mean Weight
			0,0	0,0	0,0	0,0
			0,0	0,0	0,0	0,0
			0,0	0,0	0,0	0,0
			0,0	0,0	0,0	0,0

Balance reference (with plate)				
Ref.	Weight 1	Weight 2	Weight 3	Mean Weight
7000				#DIV/0!
10000				#DIV/0!

peso filtro	ore
[g]	[h]
#DIV/0!	1,5

Figure 5.1: Weighting table

Accumulation, stabilization and weighting phases (steps 2, 3, 4) are performed several times until the balance point is not reached (or eventually the filter is clogged). Up to this point the accumulation procedure is almost completed: only the last step (regeneration phase) has to be performed.
During this step the engine works for about 2 hours at rated power, that allows to realize the natural regeneration thanks to the temperature levels higher than 400 °C (figure 5.2). In red is reported the engine fixed speed value during the regeneration phase, while in green, blue and violet are represented the temperatures at the DOC, SCR and DPF levels respectively.

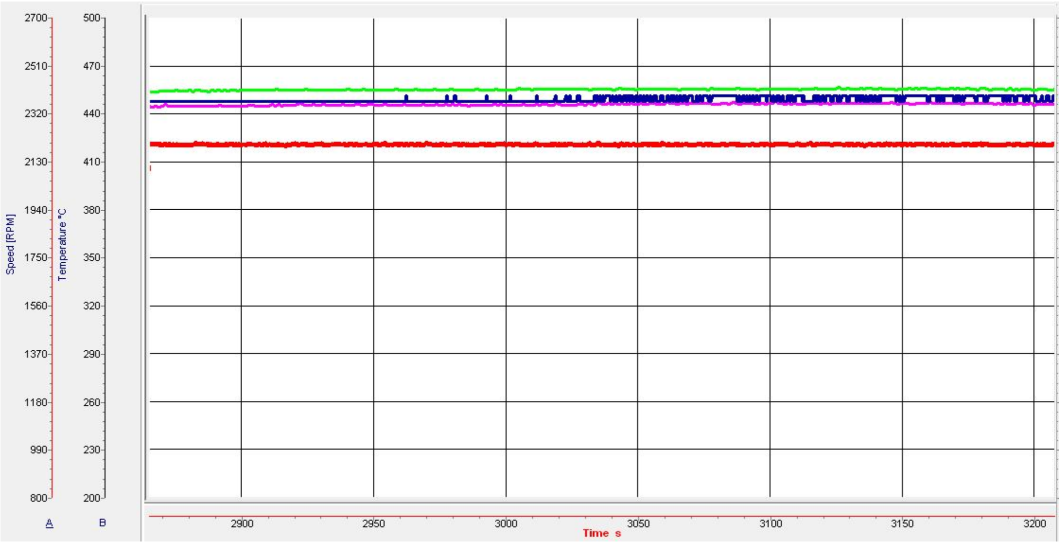


Figure 5.2: Regeneration temperatures

It is possible to notice that the temperature in the DPF zone is lower than that at the SCR even if the two components are physically placed in the same canning with the exhaust gases that should be warmer at the DPF level. The increment of temperature at the SCR level can be explained by the fact that the soot is oxidized at the DPF level releasing a certain amount of heat. This oxidation reactions are promoted by DPF catalytic coating.
After the last step the DPF can be weighted again in order to obtain the zero-weight and in this way starting again a new soot accumulation procedure. The zero-weight of the DPF, after the development of a certain number of soot accumulation tests, increases. This is due to the fact that a certain amount of ash is accumulated inside the DPF filter, as a consequence of the soot oxidized during the regeneration procedure. This ash quantity cannot be eliminated but its included in the DPF zero-weight.

5.2.1 Ash estimation

The oil consumption derives mainly from the combustion process inside the cylinder. The soot produced from oil combustion is counted as other soot produced by normal combustion, on the contrary the ash is something that is caught on the DPF filter and due to its physical structure, as it has been seen before for the ash deriving from soot oxidation, it is not able to be involved in the regeneration process. As a general value it is possible to assume that the 1 % of the oil is constituted by ash, that derives from crude-oil residuals that are not refined. Of this 1 % the 70 % is trapped inside the DPF filter. This is an experimental measurement of ash.

$$Ash = OilConsumption \cdot hrs \cdot 0.007 \tag{20}$$

(20) is the esperimental formulation, expressed in grams, used to evaluate the ash contribute from oil consumption. Furthermore, two successive zero weights will not be equal, but the last will be higher due to the ash.

5.3 Soot accumulation tests performed

In the present section it will be reported the cycles performed in the endurance cell and the corresponding soot accumulation results.

5.3.1 NRTC cycle

The first cycle performed is the NRTC transient (figure 5.3). This profile has been employed for two soot accumulation tests: in the first one the KDI 3404 StageV engine has been equipped with an ECU calibration that provide 105kW at 2200 rpm, while in the second one a 75 kW at 2500 rpm ECU calibration is used.

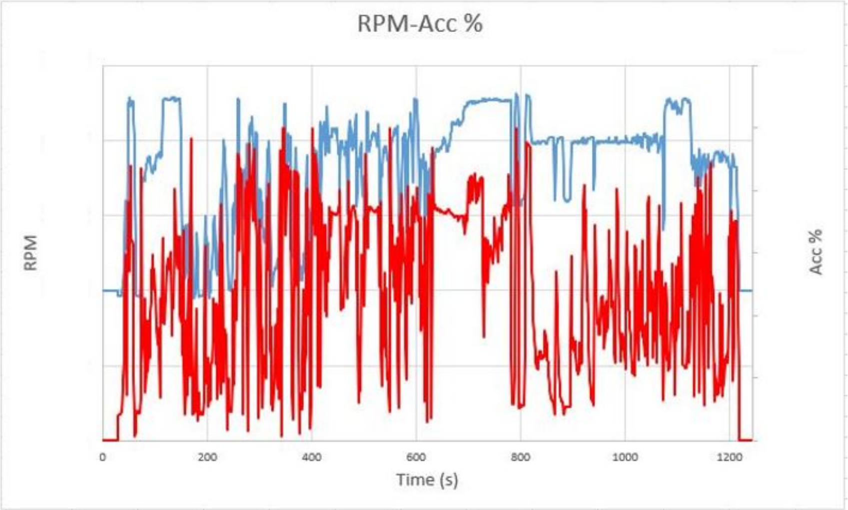


Figure 5.3: NRTC cycle

By using the more powerful ECU calibration the NRTC transient cycle has been repeated twice, in order to check if the results obtained the first time were correct, with a complete DPF regeneration in between. It is important to underline that, with the aim to compare the DPF deposits, the boundary conditions, in terms of exhaust gases at DOC and DPF inlets, have to be the same. In figure 5.4 has been reported the comparison between the temperatures at the DOC inlet and at the DPF inlet evaluated on the two NRTC transient cycles repeated. As can be noticed the two temperatures have the same level, this means that the cycle results are comparable.

Figure 5.4: Exhaust gases temperatures on DOC and DPF with NRTC transient cycle

In figure 5.5 is shown the soot accumulated, measured in grams over volume, on the DPF along 120 hours of NRTC transient cycle. In blue it has been reported the weighted soot by subtracting the ash contribute coming from the oil consumption, while in gray the weight of the soot accumulated involves the ash contribute. Moreover it is not shown the y scale, but it is the same for all the charts, so that it is possible to compare results. It can be noticed, in figure 5.5, a steep increase in the initial 25 hours, then the value of grams over liter reaches the balance point and it is stabilized.

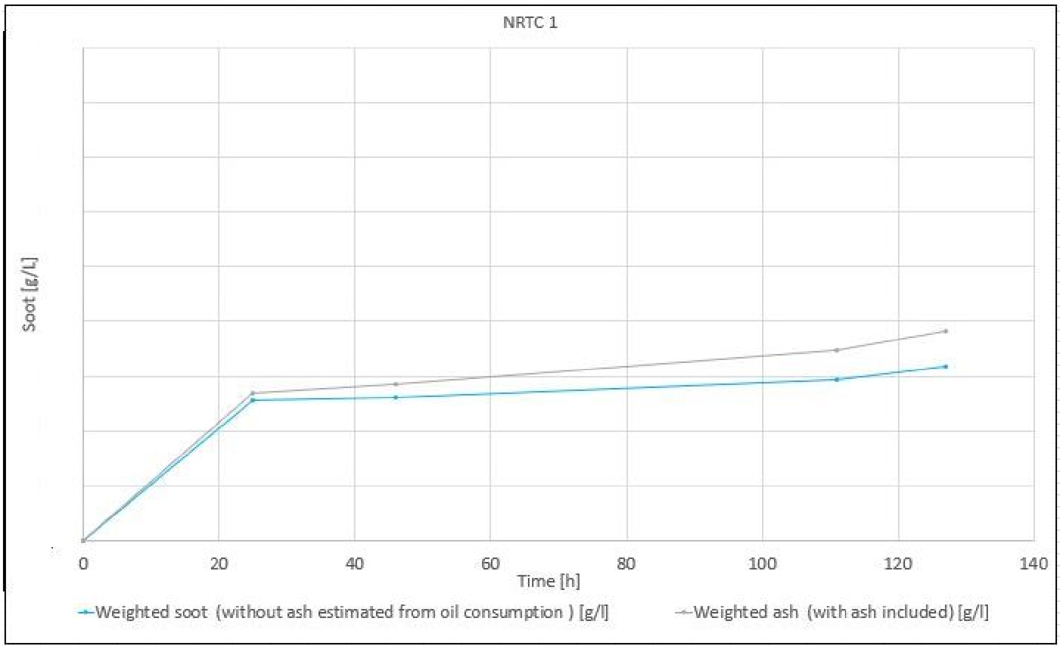


Figure 5.5: Soot accumulated on NRTC 1

In order to replicate the fast and steep accumulation of the first 25 hours, it has been replicated the same soot accumulation test, after the regeneration of the DPF filter, performed with two hours of engine power condition. The test has had the same total duration and the results are reported in figure 5.6.

As can be noticed by comparing figure 5.5 and 5.6 the soot accumulated in 25 hours is completely replicable. Then the measured value of accumulated soot becomes stable and it presents the same pattern that takes to reach the balance point immediately after 25 hours.

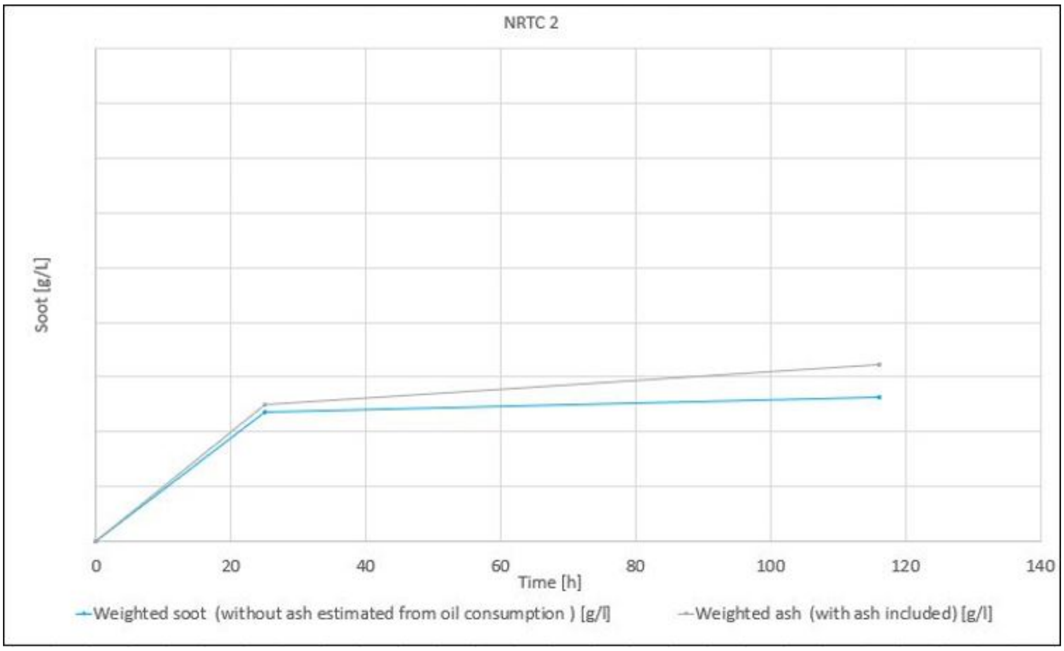


Figure 5.6: Soot accumulated on NRTC 2

A further NRTC cycle has been tested with power reduced calibration that gives 75 kW at 2500 rpm. The soot accumulated along 120 hours is reported in figure 5.7. The balance point has been reached with a value slightly higher than the one obtained with 105 kW ECU calibration.

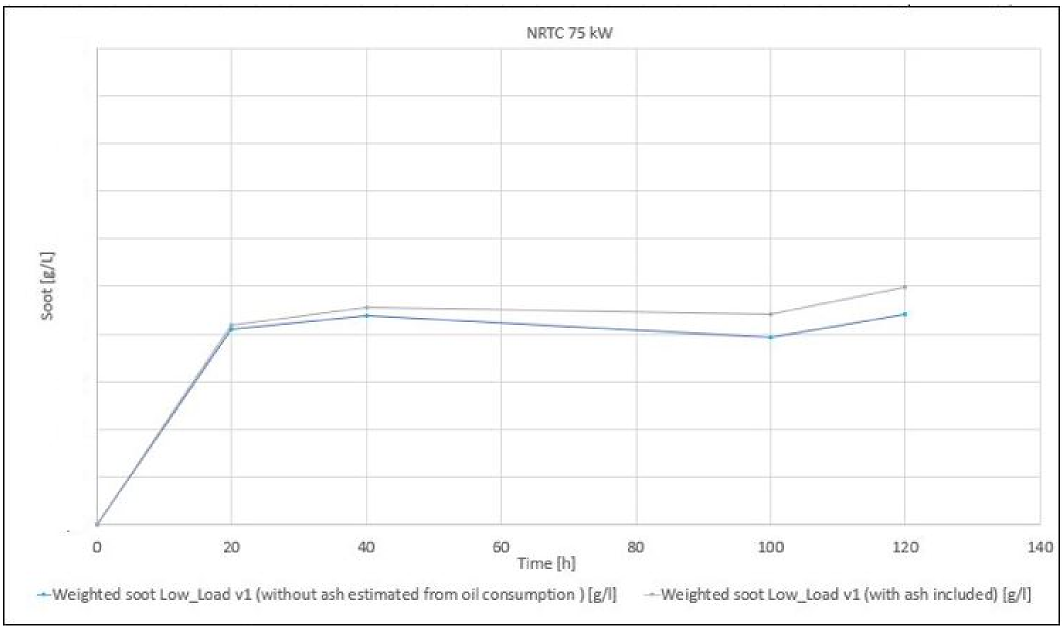


Figure 5.7: Soot accumulated on NRTC with a power reduced calibration

5.3.2 Low Load cycles

In order to perform a test that involves engine operating conditions with higher smokiness and lower exhaust gas temperatures a low load transient cycle has been used. For these causes this cycle, reported in figure 5.8, is more severe for soot accumulation respect NRTC transient one.

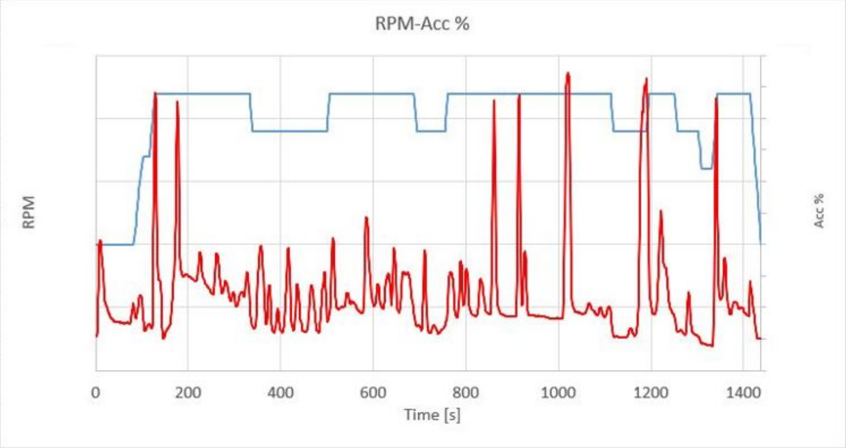


Figure 5.8: Low load version 1

It is possible to operate a comparison between exhaust gas temperature at DOC and DPF levels between NRTC cycle and Low Load cycle version 1. From figure 5.9 it is possible to observe that the temperature levels, both on DOC and DPF, are lower on the Low Load version 1 cycle, green and orange lines respectively (with red and blue lines are represented the DPF and DOC temperatures by using the NRTC cycle). The average value of the exhaust gases temperature at DOC level decrease from 290 ° to 272 °C, while DPF temperatures pass from 287 °C to 268 °C. Due to lower temperature levels the passive regeneration has a lower effect.

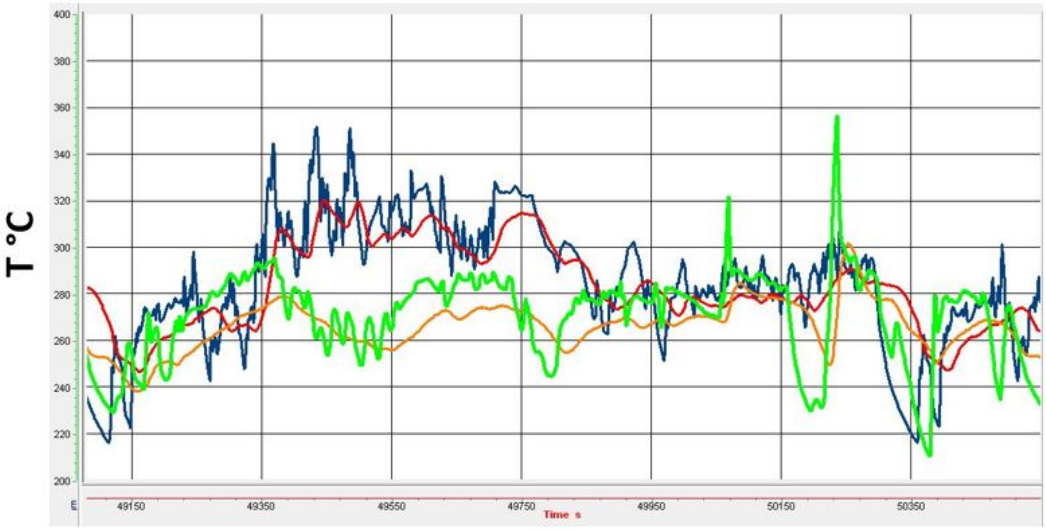


Figure 5.9: DOC and DPF temperature comparison between NRTC and Low load cycle version 1

In figure 5.10 it is possible to observe an higher accumulation of soot in the first 20 hours respect figure 5.5 and 5.6. This is due to the different engine operating points that have higher smokiness and lower exhaust gas temperature levels. The balance point is obtained with a value of accumulation that is approximately two times of the one reached using the NRTC transient cycle with 105 kW calibration.

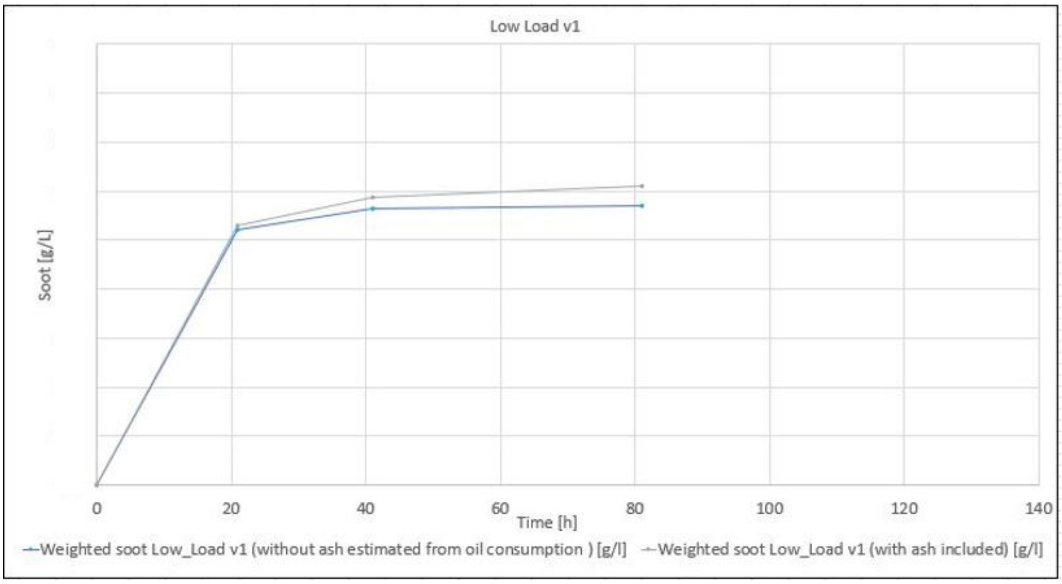


Figure 5.10: Soot accumulated on Low load v1

A second low load cycle, called version 2 (v2), has been tested in order to shift operating points towards different functioning zones. In particular this passage has been done because the purpose was to intercept operating points with the highest smokiness and as a consequence replicate the most critical condition for the DPF soot accumulation with a risk of filter clogging.
The low load cycle version 2 used has the same pedal percentage path of the low load version 1 cycle but a decrease of engine speed over the entire cycle has been introduced. In figure 5.11 it possible to observe in yellow the new speed pattern followed by low load cycle version 2. The pedal percentages are completely superimposed.

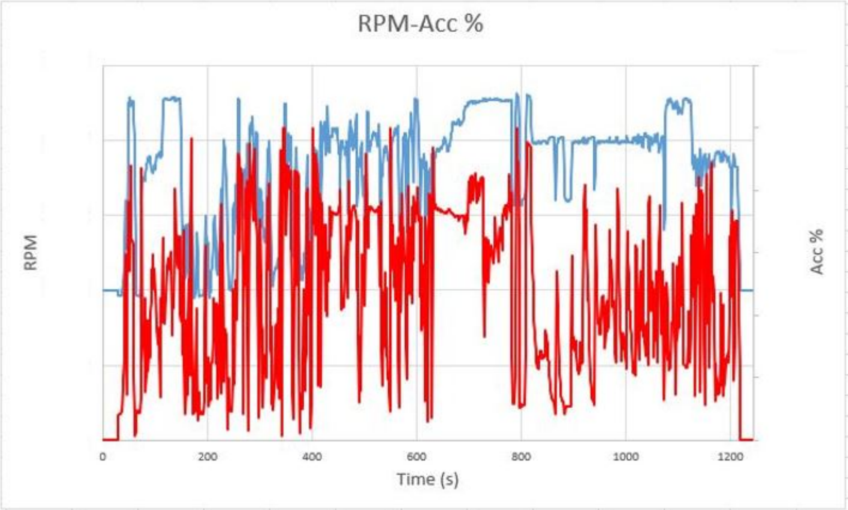


Figure 5.11: Shifted Low load v2 profile

In figure 5.12 it has been reported the downshift of engine speed from the point of the view of the engine operating points. As can be noticed by the dimension of the circles, that represent the engine smoke, the new operating points involves a region with a higher smokiness.

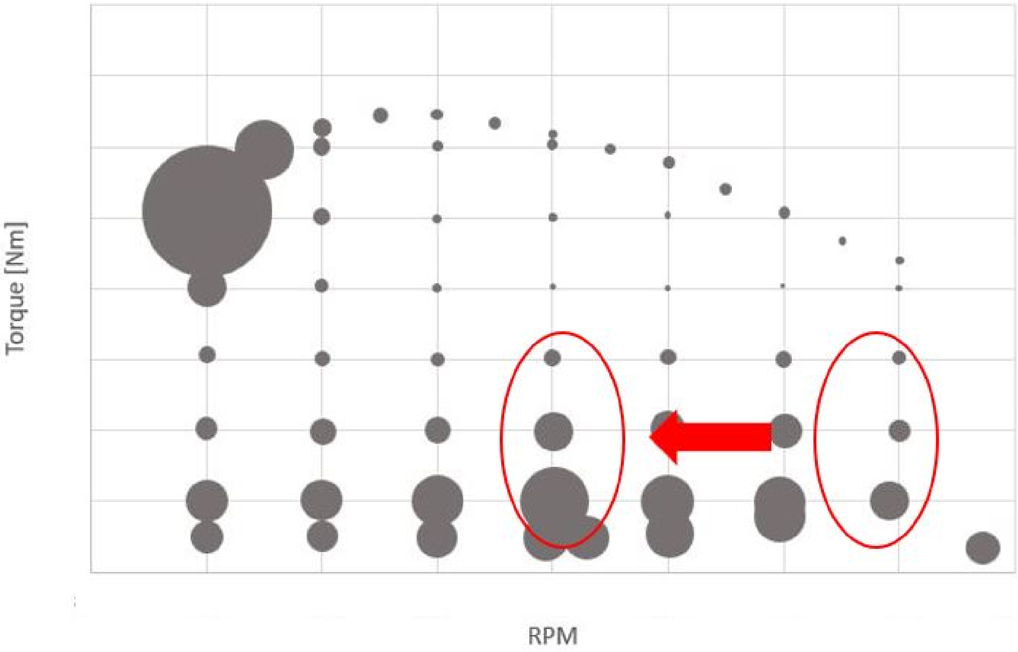


Figure 5.12: Engine operating points downwards shift

The result of the soot accumulation test has been represented in figure 5.13. By analyzing the graph it is possible to observe that the balance point is achieved with a value higher than the one obtained with Low load v1 cycle.

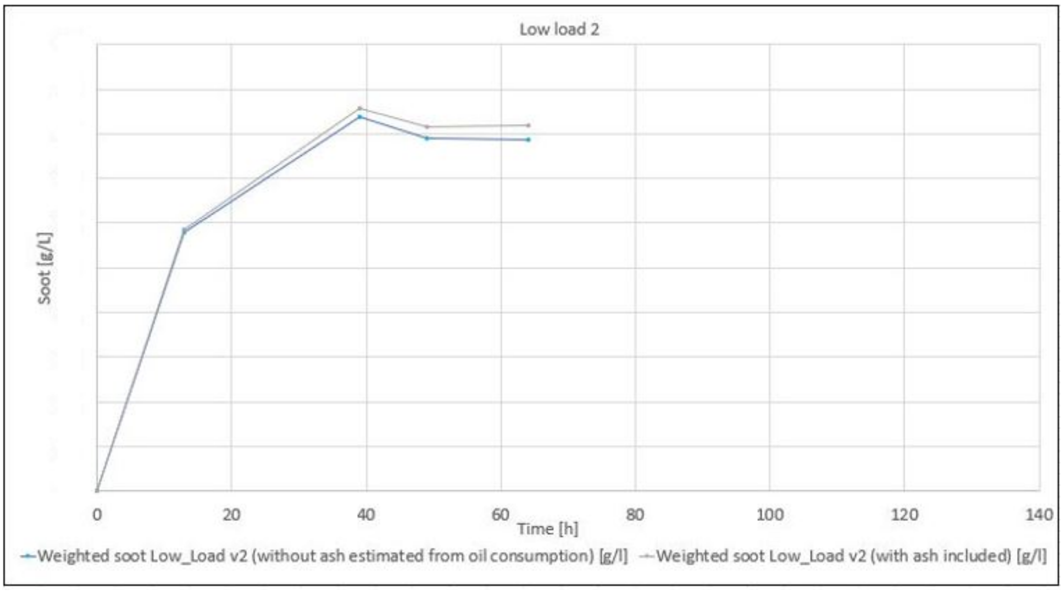


Figure 5.13: Soot accumulated on Low load v2

At the end of this test the DPF was almost clogged. This condition is extremely dangerous, but the purpose of the low load v2 is exactly to reproduce the most dangerous DPF soot loading.

5.3.3 Vehicle cycle

Until now all the cycles tested have been performed in the endurance cell. In order to know if the low load cycle used represents a real one, a typical machine low load cycle has been executed and a comparison of the two cycles has been performed. In figure 5.14 it has been represented the low load cycle performed by the machine.

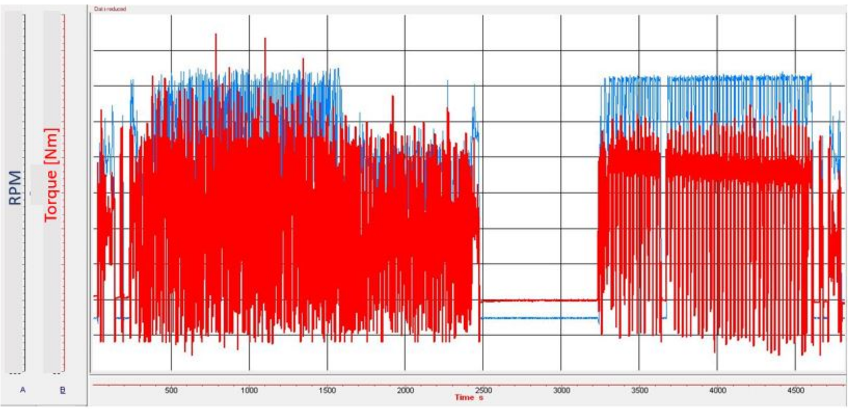


Figure 5.14: Machine cycle

By comparing the exhaust gases temperature at DOC and DPF levels it is possible to notice in figure 5.15 that both these temperature levels are higher on the machine cycle respect to low load v2 cycle. Blue and red lines represent respectively the DOC and DPF temperature levels during the machine cycle, while green and yellow lines indicate the DOC and DPF temperatures of the Low load v2 cycle.

Figure 5.15: DOC and DPF temperature levels

This fact is positive because in the endurance cell it has been used a cycle with lower temperature levels and a correspondent lower passive regeneration effect. To support the lower exhaust gases temperature levels on low load cycle in figure 5.16, the torque comparison on the two cycles shows as on the low load machine cycle (red line) the engine torque points have an higher value respect to low load v2 (green line).

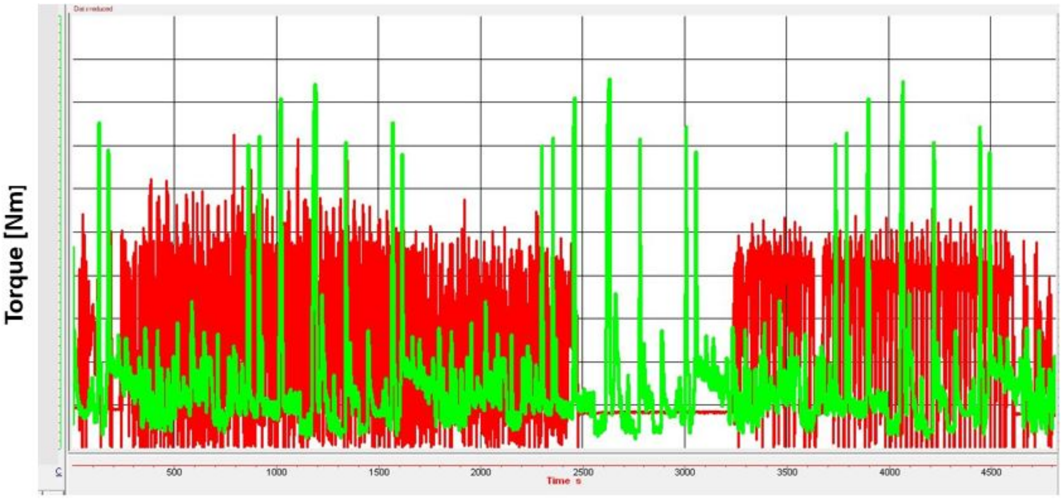


Figure 5.16: Torque levels on machine cycle and Low load v2

On the other hand it is important to underline that the after treatment system configuration on the machine is different respect to the one used in endurance cell. In particular the distance of the after treatment system from the exhaust manifold is lower on the machine configuration than on the configuration of the endurance cell. This fact can also explain the higher temperature levels on DOC and DPF in the machine configuration.
As a conclusion, the position of the after treatment system has an effect on the temperature levels, but what ensure that the cycle tested in the endurance cell is more severe and representative of what concern low load condition are the lower engine speeds (figure 5.17 , in blue has been reported the machine cycle speeds, while in yellow is represented the Low load cycle v2 speeds) and lower torque conditions (figure 5.16).

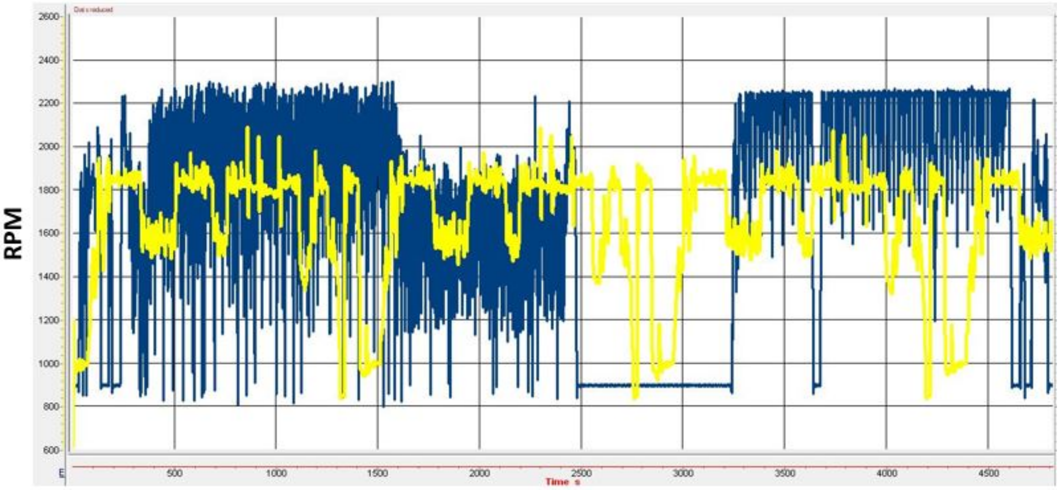


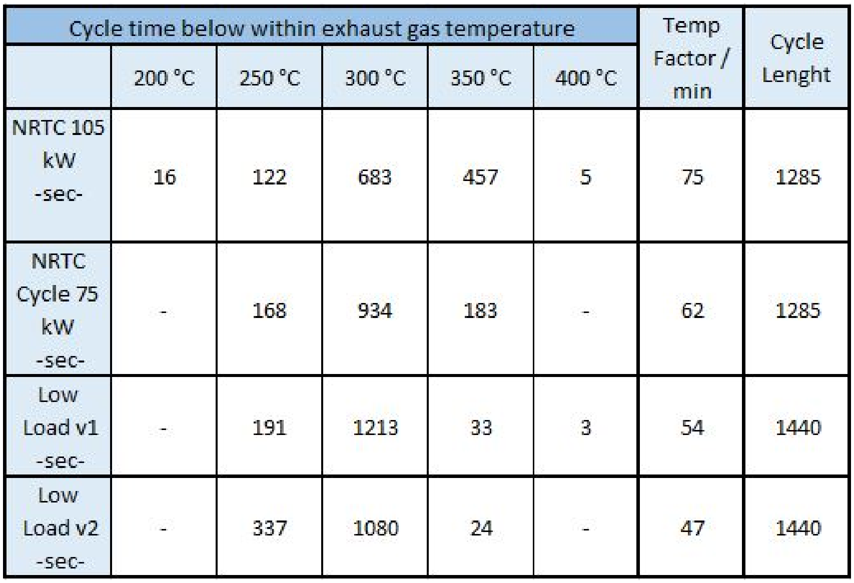
Figure 5.17: RPM levels on machine cycle and Low load v2

5.3.4 Temperature factor

A generic temperature factor can be calculated for each type of duty cycle to quantify the effectiveness of exhaust gases temperature profile on soot burn-off capability and it is used to compare different cycles. This factor is more precise respect the average exhaust gas temperature level. A comparison between NRTC and Low load cycle exhaust gas shows a difference of 20-30 °C, therefore it would be possible to say that the two cycles are similar. In reality, by looking with more attention the working points, the Low load profile has exhaust gas temperature levels always in the zone of 275 °C, while the NRTC cycle has different zones where the exhaust gas reaches 350-400 °C. For this reason is not possible to say that these two cycles are similar.
The formula used to calculate this factor derives from empirical experience and is based on the fact that passive regeneration, higher burn-off rate than soot imput, occurs firstly above 300 °C. From testing experience it has been observed that soot burn-off rate increases generally with a factor of 2 for every 50 ° C exhaust gas temperature rise.
The formulation can be written as:

$$\begin{aligned} Tempfactor = A \cdot Time(300°C) + 2 \cdot A \cdot Time(350°C) + \\ 4 \cdot A \cdot Time(400°C) + 8 \cdot A \cdot Time(450°C) + 16 \cdot A \cdot Time(500°C) \end{aligned} \tag{21}$$

By analyzing (21), with "$Time$"($°C$) is indicated the temporal period in which the exhaust gas temperature is below the temperature threshold in brackets. Moreover "A" is a factor that has been assumed equal to 1. In figure 5.18 has been reported the temperature factors, normalized over the cycle lenght, obtained for the cycles tested.



Cycle time below within exhaust gas temperature						Temp Factor / min	Cycle Lenght
	200 °C	250 °C	300 °C	350 °C	400 °C		
NRTC 105 kW -sec-	16	122	683	457	5	75	1285
NRTC Cycle 75 kW -sec-	-	168	934	183	-	62	1285
Low Load v1 -sec-	-	191	1213	33	3	54	1440
Low Load v2 -sec-	-	337	1080	24	-	47	1440

Figure 5.18: Temperature factors

Cycles with higher Temperature factors have a higher regeneration attitude and therefore, a lower balance point is expected.

5.3.5 Results obtained

In order to compare the results obtained it is important to consider the balance points obtained through the cycles tested. In figure 5.19 a comparison between these values has been performed.

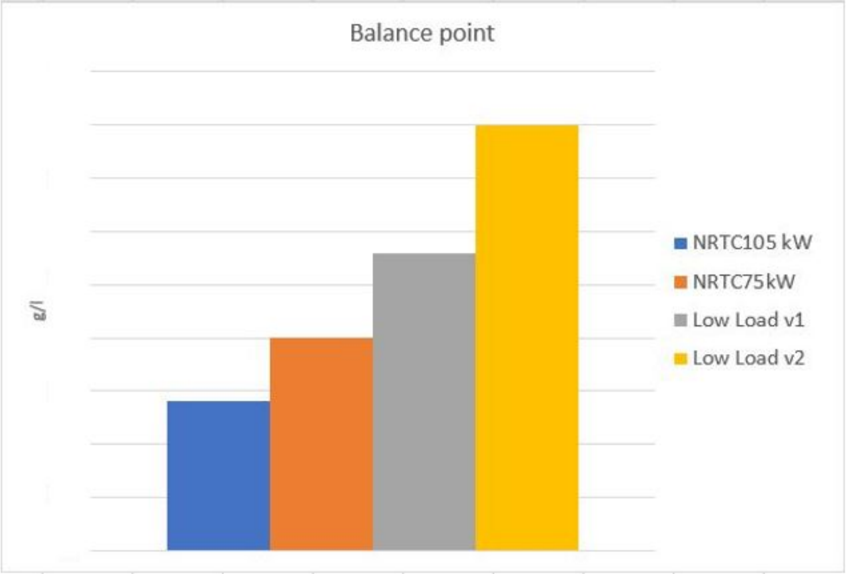


Figure 5.19: Balance points

Another important source of information to analyze the results comes from figure 5.18. By comparing the temperature factors (figure 5.18) with the balance points graph, (figure 5.19) it is possible to notice that the NRTC cycles, with both the engine calibrations, present the highest temperature factors. As a consequence, in figure 5.19, the balance points is reached with the lowest values of soot accumulated. In presence of an high temperature factor, the balance point is reached with a low value of soot accumulation. This means that there is an observable effect of natural regeneration. On the other hand, in presence of a low temperature factor, the balance point is obtainable with an high value of soot accumulated. The natural regeneration has a very poor effect and consequently there is a real risk of DPF clogging.

6 Urea deposits inside the SCR system

6.1 Introduction

This part of the activity is focused on the analysis and characterisation of possible urea deposits inside the selective catalyst reduction system (SCR) of a KDI 3404 Stage V engine. For what concern the SCR system the urea is injected through a low pressure injector within the SCR mixer, where the urea spray is broken up and mixed with the exhaust gas mass flow. This primary spray is converted subsequently into isocyanic acid and ammonia. Droplets with diameter bigger than 50-100 μm do not usually decomposes completely, in particular at low exhaust temperatures before impinging on mixing unit walls. As a consequence, on these surfaces a wall film is formed (figure 6.1). Due to stripping phenomena, secondary droplets can be constituted or with another mechanism of water evaporation and molten urea decomposition, from the thin wall film, ammonia and isocyanic acid are formed.
During all these processes, unexpected solidification and deposition reactions take place, which can form urea deposits.

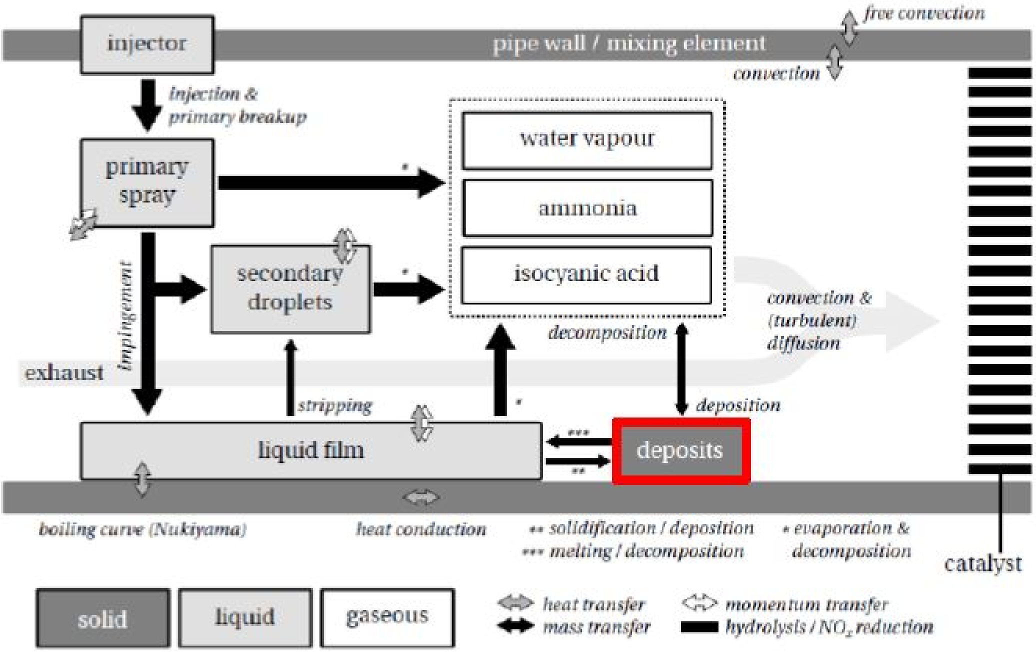


Figure 6.1: Model of SCR Urea deposits

During the engine functioning, depending on operating conditions, the deposits can build up, clogging up partially the mixing zone of the SCR, or dissolve completely. One of the main purpose of the activity has been to identify critical zones in the mixing section considering the deposit growth. An identification of robust dosing area has been also performed, by providing the maximum urea dosing amounts for SCR calibration based on stationary deposit tests. Moreover, by using worst case load profiles, an investigation of deposits growth during transient operations has been done. Finally it has been verified the urea deposits removability by using the active DPF strategy regeneration.

6.2 Urea deposits measuring methods

There are different options how to evaluate the urea deposits build up in the mixing section: on the engine dyno or on an hot gas test bench. In both cases the set up of the after-treatment system has to be identical to the vehicle layout, at least from the DOC outlet to the exit of the SCR brick. The setup used in Kohler foresaw the use of the engine dyno.

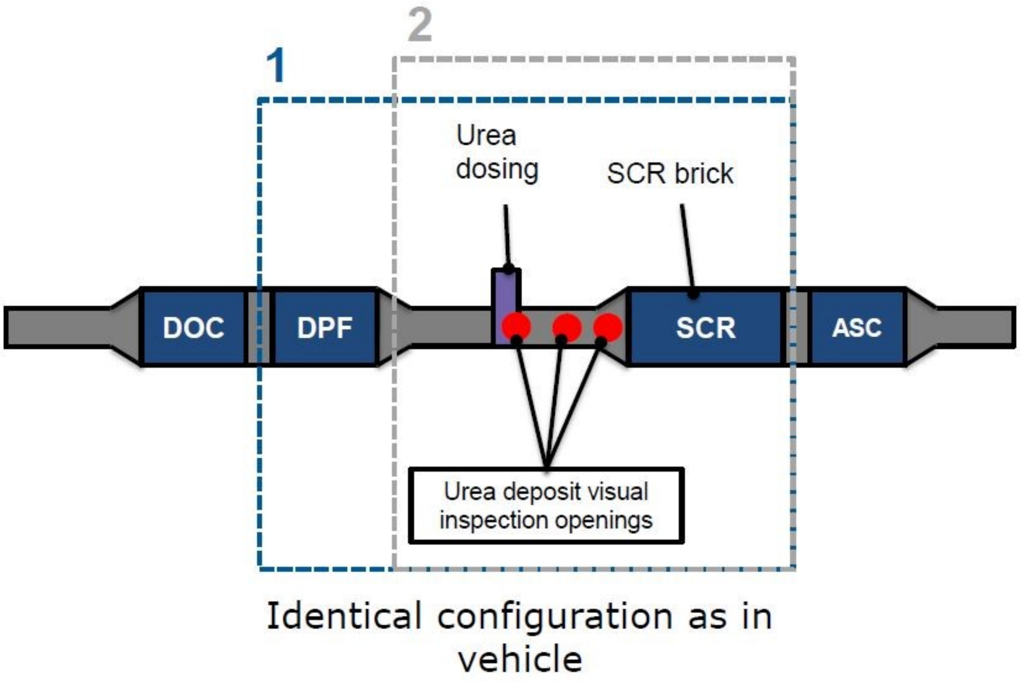


Figure 6.2: ATS configurations

From figure 6.2 it is possible to notice the presence of two possible design variants for the after treatment system. By using the same ATS employed for soot accumulations tests, the variant 1 has been preferred with all the components available in order to have the same boundary conditions as on the vehicle. Visual inspections via endoscope has been performed from the urea injector hole by removing every time the injector, in order to have a general overview on the mixing section. During the tests, a range of parameters of the

DCU has been considered: NO_x concentrations, urea dosing mass flow rate, upstream SCR temperatures, pressures.

6.3 Identification of robust dosing area

The first part of the analysis has involved steady state deposit tests. The deposits formation is strongly dependent on the hardware selected (canning, mixer, doser) and on the boundary conditions. As an example, in figure 6.3, has been reported a map that underlines the main parameters combination that define critical functioning zones for urea deposits.

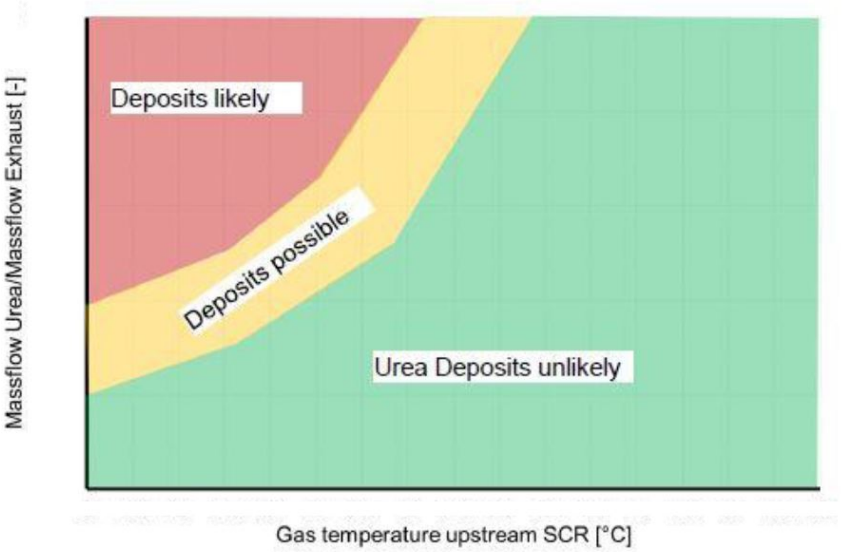


Figure 6.3: MassflowUrea/MassflowExhuast vs Temperature upstream SCR defines critical urea deposit zone

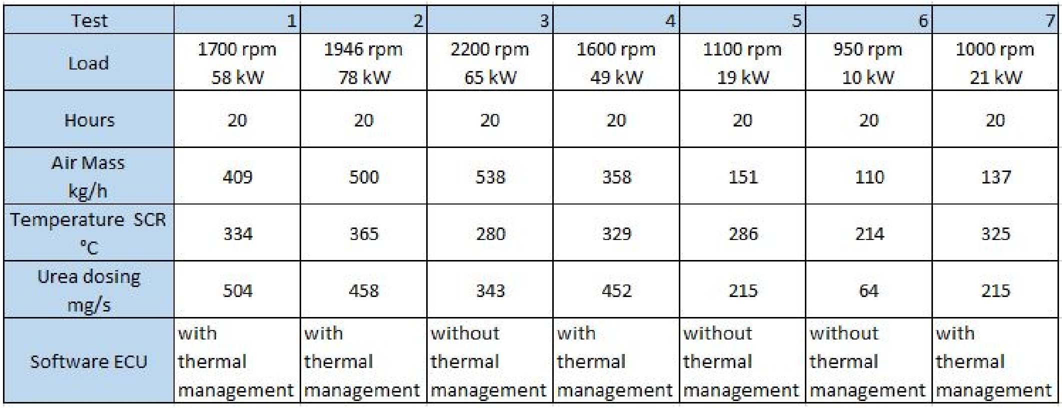
In green it is possible to reach the maximum dosing amount without urea deposits built up. In yellow the urea dosing amount that generates deposits built up at acceptable level for short term operation. In red zone the deposits grow above acceptable level.

The steady state operating points selected for the tests perfomed in Kohler needs to cover low and high exhaust mass flows and temperatures upstream SCR from 180-270 °C. The third target searched is the urea dosing amount. The procedure adopted for stationary functioning points forsees the choice of the operating point in terms of speed, with an increase of engine torque until SCR inlet temperature is on target. The operating point is kept until thermal stabilization is obtained. When SCR upstream temperature is achieved a specific urea dosing amount is injected. The stationary functioning condition is held for a certain amount of hours. At the end of the test urea injection is stopped and the engine is immediately switched to minimum speed and zero

torque for a certain time interval until SCR inlet temperature is below 60 °C. Finally the visual inspection can be performed. It is important to underline that pictures of different operating points can be compared to each other, thus pictures shall be taken at the same orientation, position and angle, moreover the brightness has to be identical.
In order to refresh the SCR from urea deposits it is possible to perform manual DPF regenerations of 15 minutes. These procedures allow to obtain exhaust gas temperature higher than 500 °C. After each regeneration an SCR inspection is done to check the complete deposits removal. If not all deposits are removed it is necessary to repeat ATS refresh procedure. This procedure allows to validate if deposits can be removed during regeneration under critical conditions.

6.4 Tests on stationary points

Stationary tests has been performed on KDI 3404 Stage V it has been selected seven functioning points. Each one has been performed for 20 hours.

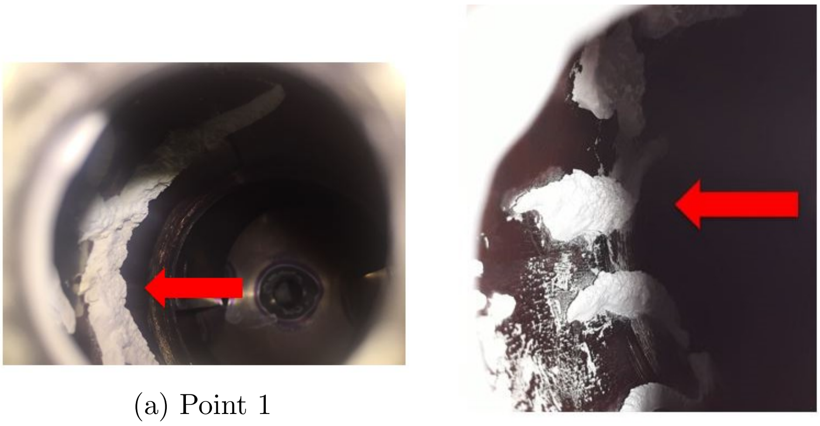


Test	1	2	3	4	5	6	7
Load	1700 rpm 58 kW	1946 rpm 78 kW	2200 rpm 65 kW	1600 rpm 49 kW	1100 rpm 19 kW	950 rpm 10 kW	1000 rpm 21 kW
Hours	20	20	20	20	20	20	20
Air Mass kg/h	409	500	538	358	151	110	137
Temperature SCR °C	334	365	280	329	286	214	325
Urea dosing mg/s	504	458	343	452	215	64	215
Software ECU	with thermal management	with thermal management	without thermal management	with thermal management	without thermal management	without thermal management	with thermal management

Figure 6.4: Tests on stationary points

Test points N°3 - N°5 -N°6 have upstream SCR temperatures that are not possible to be reached during a stabilized test due to the thermal management of the throttle valve, at the intake manifold. Tests in the cited points have been done with a dedicated calibration with open throttle valve. Test point N°7 is equal to test point N°5 but it has been executed with a standard calibration, that implies thermal management and as a consequence an higher upstream SCR temperature. The thermal management is a specif strategy applied by the throttle valve in order to reduce air into combustion chamber and as a consequence increase the exhaust gas temperature.
Tests N°1 and N°4 have similar results, in particular it has been obtained

helical deposits on the upper half of the mixer. In figure 6.5 is presented a comparison of the two tests.

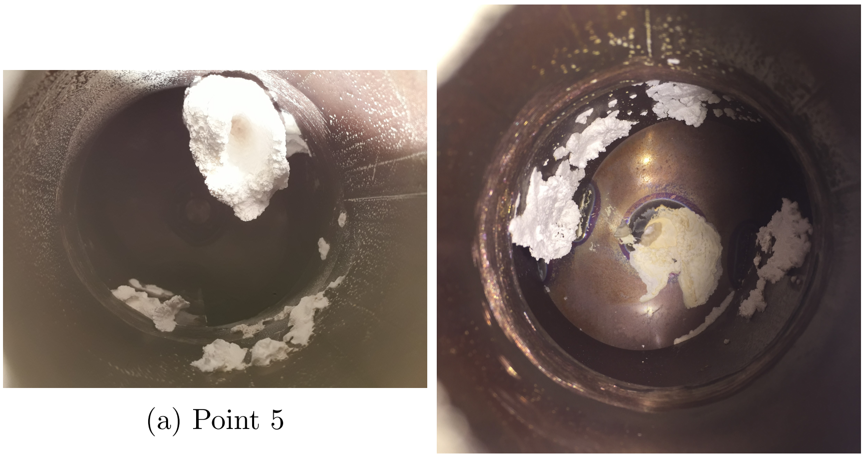


(a) Point 1

(b) Point 4

Figure 6.5: Point 1 and point 4 comparison

Also tests N°5 and N°6 have comparable results, many deposits have been observed (Figure 6.6) on the bottom of the mixer especially at the inlet port DPF side.



(a) Point 5

(b) Point 6

Figure 6.6: Point 5 and point 6 comparison

Test N°7, has been added to check if the standard level of temperature, due to thermal management, is sufficient to avoid urea deposits. As can be observed in figure 6.7 the result is positive: no deposits are observable.

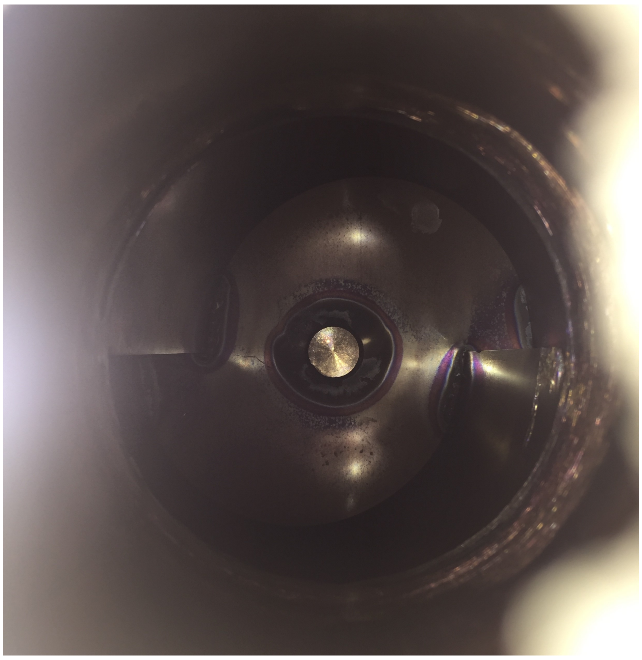


Figure 6.7: Point 7

At the end of the stationary point tests it has been chosen the most critical result, in particular test N°1, and it has been performed a long deposit test with a duration of 100 hours. The result is presented in figure 6.8.

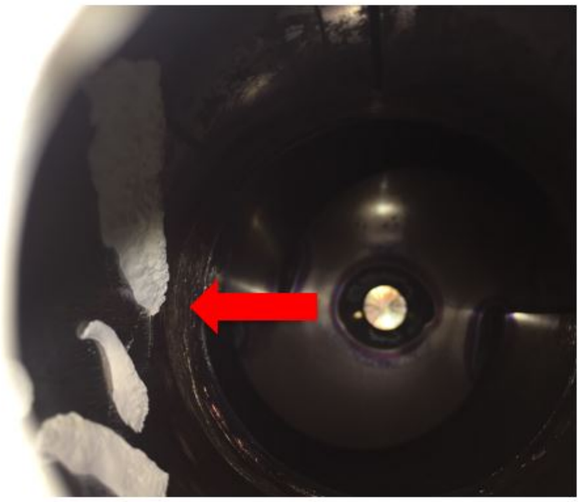


Figure 6.8: Point 1 after 100 hours

It is possible to observe, in figure 6.8, that the deposits are similar to the test conducted for 20 hours. The result is interesting because no observable growth of deposits takes place. This means that deposits are strongly influenced by how the initial layer of liquid film, that it's the precursor of deposits, impacts on SCR internal wall. This phenomena is deeply stochastic and dependent on initial conditions. In order to verify what it has just said, stationary test N°1 has been repeated for 20 hours. In figure 6.9 it is possible to observe how the result doesn't present deposits in the characteristic zone analized.

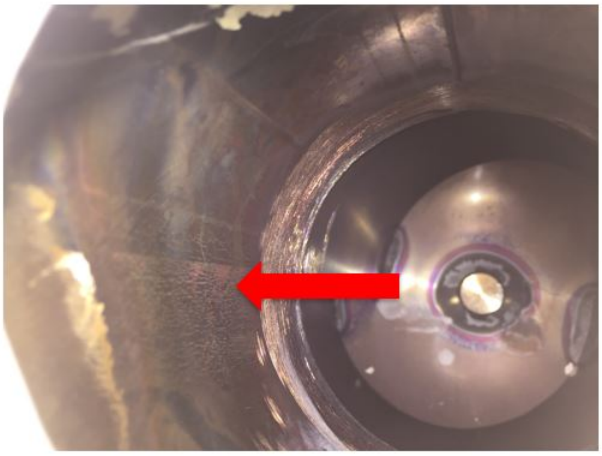


Figure 6.9: Point 1 repeated

Other deposits have been observed in different zones of the SCR mixer, but deposits obtained in the first 20 hours test haven't been replicated.
This result has allowed to increase the urea dosing limits in certain SCR functioning conditions, defined by upstream SCR Temperature (°C) and exhaust mass flow (kg/h), that before this type of analyis had preliminary and lower limits due to the uncertainty about deposits formation. In figure 6.10 can be observed the first urea dosing map: white, yellow and red dots, with a negative number inside, indicate that the dosing needed is higher than the limit imposed. Green dots represent functioning condition where it is possible to inject the wanted urea quantity.

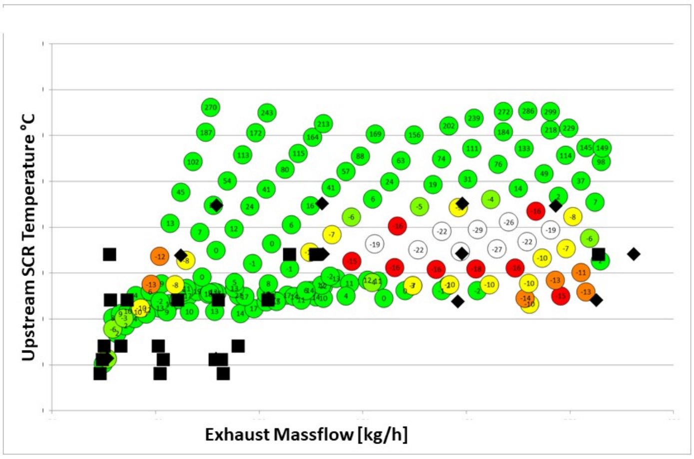


Figure 6.10: Urea dosing map limits

In figure 6.11, where the updated urea dosing map is reported, it is possible to observe that, thanks to positive results of deposit analysis , the limits have been increased and all the dots have become green. The new dosing values had been introduced in the ECU improving the dosing performances of the engine.

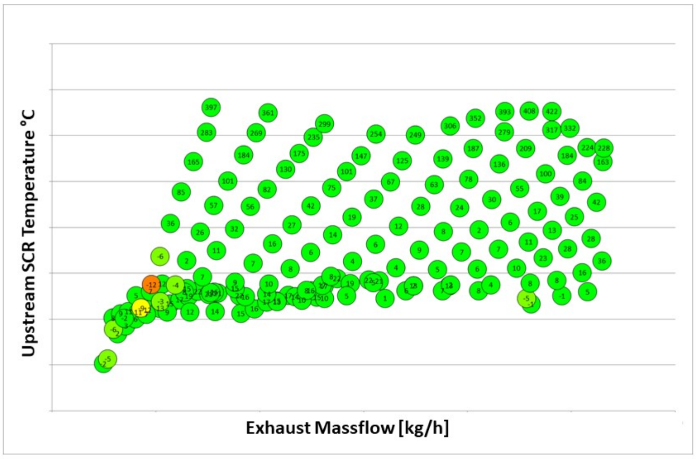


Figure 6.11: Urea dosing map limits updated

6.5 Tests in transient operations

The goal of transient deposit tests is the confirmation of new urea dosing limits from steady state deposit analysis. Test procedure should evaluate level of urea deposit build up during transient operation. Furthermore it is important to analyze the removability of urea deposits during regeneration phase. The engine functioning points that form transient cycle used, reported in figure 6.12, has been suggested by the SCR supplier. They involve 4 different loads and they are critical because are across (above and below) the threshold temperature for urea dosing. So it is, overall, a cold cycle.

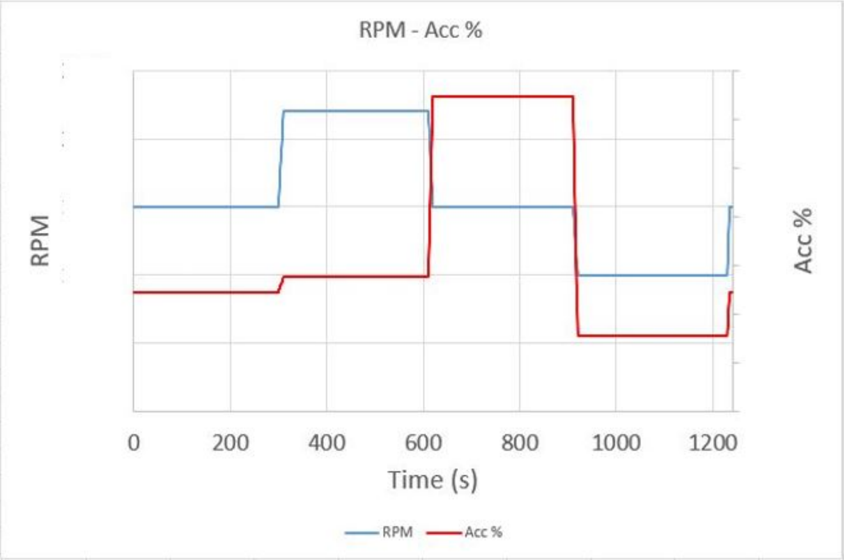


Figure 6.12: SCR supplier cycle

The goal of the activity is to reach the worst dosing case. Differently from stationary tests, where urea dosing, expressed in $\frac{mg}{s}$ was imposed equal to a specific value, with transient cycle the generic urea dosing limitation in SCR calibration has been shifted towards an higher threshold. This operation corresponds to set α parameter, defined as

$$\alpha = \frac{NH_{3_{ppm}}}{NO_{x_{ppm}}} \tag{22}$$

equal to 2. $NO_{x_{ppm}}$ parameter is read by the NO_x sensor at the after treatment system inlet. By fixing α, the output is $NH_{3_{ppm}}$ that is converted by (23)

$$NH_{3_{ppm}} = \frac{\dot{m}_{NH_3} \cdot 10^{-3}}{\frac{\dot{m}_{exh}}{3{,}6} \cdot \frac{M_{NH_3}}{M_{air}}} \tag{23}$$

into a mass flow of NH_3, expressed in $\frac{mg}{s}$.
In the second step, α parameter has been further increased to 10.
These functioning conditions, in particular with α=10, allow to works always on the maximum urea mass flow thresholdset in the ECU. In 6.13 figure has been reported the comparison between the maximum urea injectable and the value of urea injected with α=2 over the transient cycle.

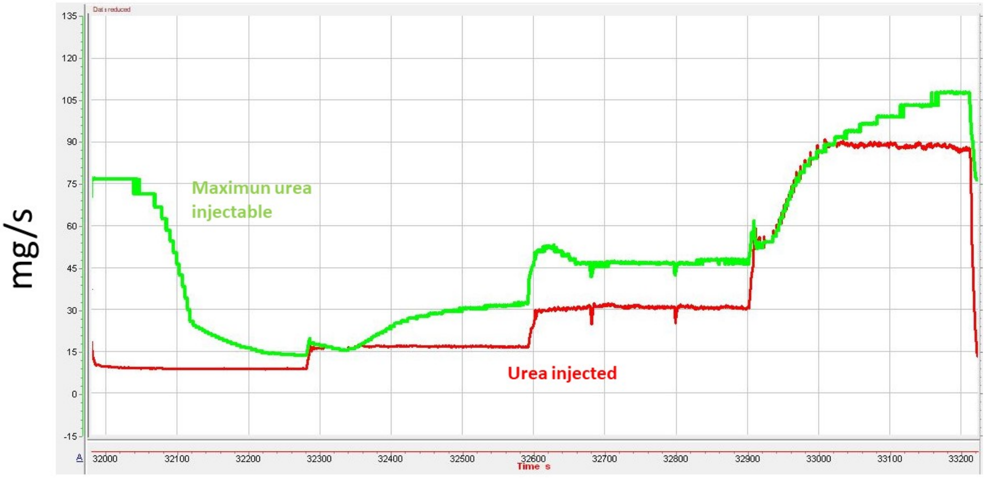


Figure 6.13: Urea injected vs. urea injectable with α=2

As can be noticed only in certain functioning points the maximum threshold is reached. In figure 6.14 the same parameter comparison has been reported but with α setted to 10. The maximun urea threshold is completely superimposed to the urea injected.

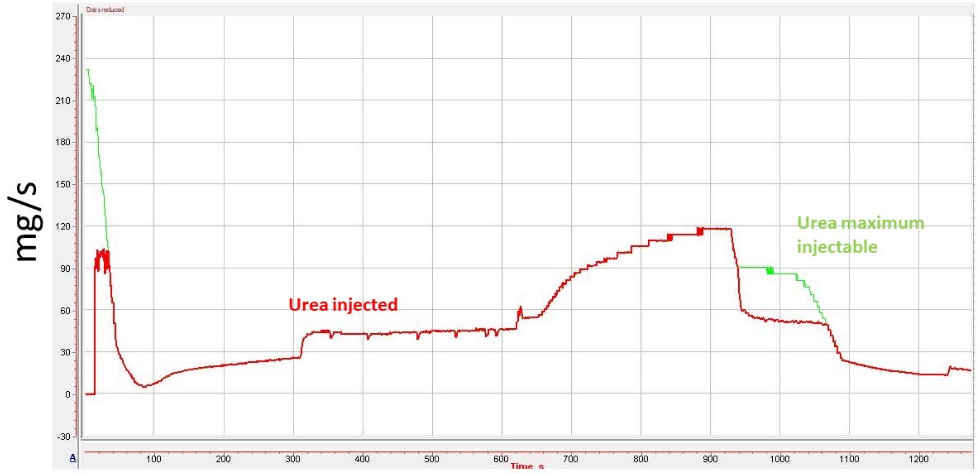


Figure 6.14: Urea injected vs. urea injectable with α=10

The visual inspections, with α=2, has been performed at 20 hours and 40 hours. No visible deposits have been observed, as can be noticed from figure 6.15.

Figure 6.15: SCR inspection after 20 hours with α=2

The visual inspection after 40 hours hasn't revealed a growth of urea deposits (figure 6.16).

Figure 6.16: SCR inspection after 40 hours with α=2

By increasing α=10, the visual inspection, performed after 20 hours, 40 hours and 90 hours, gives the results of figure 6.17, 6.18, 6.19 respectively.

Figure 6.17: SCR inspection after 20 hours with α=10

Figure 6.18: SCR inspection after 40 hours with α=10

Figure 6.19: SCR inspection after 90 hours with α=10

Few deposits are observable but their level is not comparable to stationary point tests. A so low level of deposits is a positive result because by using DPF strategy regeneration it is possible to clean completely the SCR (figure 6.20).

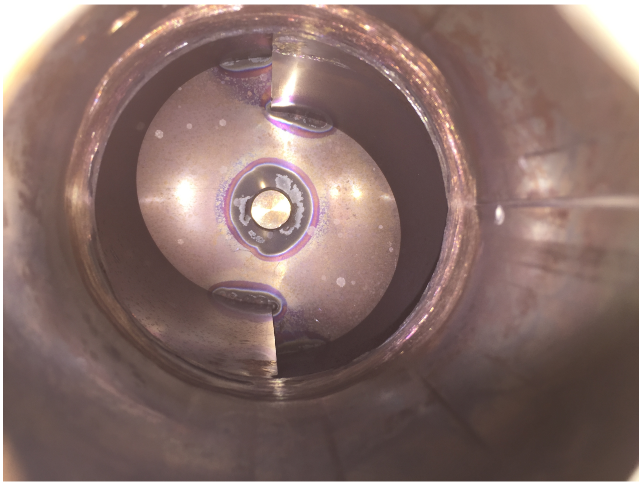


Figure 6.20: SCR mixer after DPF regeneration

7 Conclusions

Throughout this thesis it has been possible to improve the DeSOx strategy acting in the after treatment dosing control unit (DCU) of a Tier 4 Final engine. The new temperature thresholds, validated by using the loops presented in Chapter 3, allow to perform the SCR regeneration at lower temperature levels. As a consequence the techniques used to increase exhaust gas temperature, such as post fuel injections, can reach the target by introducing less fuel and for a lower time interval. These conditions provides, from the engine point of view, lower fuel consumption and reduced pollutant emissions, while it guarantees safer working conditions for the machine operator that is not exposed to high unburned fuel levels.

The works conducted on Stage V after treatament system and in particular on DPF has allowed to characterize completely the behaviour of the particle filter on NRTC cycle and low load cycles. The balance point values obtained fully reflect what was expected and they were aligned with temperature factors evaluated from exhaust gas temperatures analysis. It is importance to notice that this soot accumulation activity is only the first step of following passages. In particular a second soot accumulation will be performed by using the same cycles, but the weighting results will be compared with the output of an ECU model that will estimate the soot accumulated. The matching of these two value will guarantee if the model is tuned correctly.

For what concern deposit test the analysis gave as result an updated urea dosing map, with higher thresholds in crictical operating points. This will guarantee to have a safer limit on NO_x reduction when the after treatment system will be tested on emission test bench, without occuring in urea deposits problems.

The after treatment system used for tests on Stage V engine will be tested on emission test bench. In particular it will be analized the possible sintering problem in the DOC, where, due to excessively high operating temperatures, the small noble metal particles will clump togheter to form larger particles with a lower surface, that cause a reduced activity. The DPF system can reduce its filtration capacity due to cracks that can form inside the silicon carbide structure after repetead regeneration procedures. Eventually the ion-exchanged sites of SCR walls can lose their adsorbption capacity, this fact generate a decrease of SCR performances . All these facts will be deeply analized in order to characterize the decrease of the system efficiency respect the starting values.

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KOHLER.
IN POWER. SINCE 1920.

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