Everything about Aftertreatment Systems in the Heavy-Duty industry.

System breakdown, DPF in detail and troubleshooting of recurrent issues.

Part I

CV COMMERCIAL | AGV AGRICULTURAL | OHW OFF-HIGHWAY | marine VESSELS

jaltest DIAGNOSTICS

Contents

Easy document navigation

Introduction

After listening to our users over the past months, we decided to cover this topic in depth as we know there are many struggles around it in the industry. There is a lot said about Aftertreatment Systems but we couldn't find a compiled source of reliable information about it.

The evolution in Heavy Duty Trucks and in everything Diesel, has made it so that Diesel Particulate Filters have become the norm. But that was not always like that.

There were times, some technicians would say "The Good Old Times" where DPF's and aftertreatment systems did not exist. Times where everything was so much simpler and fixing a truck depended on your mechanical knowledge and of the experience you had. How simple life was. Now all of that has changed.

The Environmental Protection Agency (EPA) got involved and it started passing proposals first, and then laws. These laws have changed trucking forever. Nowadays every truck needs a DPF Filter, a solid Aftertreatment System and its DEF Fluid.

The difficulty here is that all of this is electronically controlled, requiring sensors, calibrations, pressure and temperature checks. This all means that for undertaking almost every repair we now need a computer.

Join us on this journey of understanding the essence of Aftertreatment Systems and how these systems relate to and affect our modern vehicles, and how we can use the right tools to run diagnostics, calibrate and repair any issue that comes up.

We have decided to divide this document into two parts as we wanted to make sure we keep things interesting for you.

Check below the content we cover in Part II:

click here

- DPF composition in detail: different kinds of Regens, Resets and Replacement of the filter.
- Maintenance of the rest of the Aftertreatment System.
- Recurrent Aftertreatment issues and how to solve them all.
- Diagnostics tool and the Aftertreatment System:
  1. Is an Aftermarket Diagnostics tool a good choice and why?
  2. Essential functionalities any tool must include.
  3. Jaltest Diagnostics and the Aftertreatment System.

I. Environmental impact of diesel engines

In a perfect world we would all wish to breathe the cleanest air. However, most of our human interactions generate emissions.

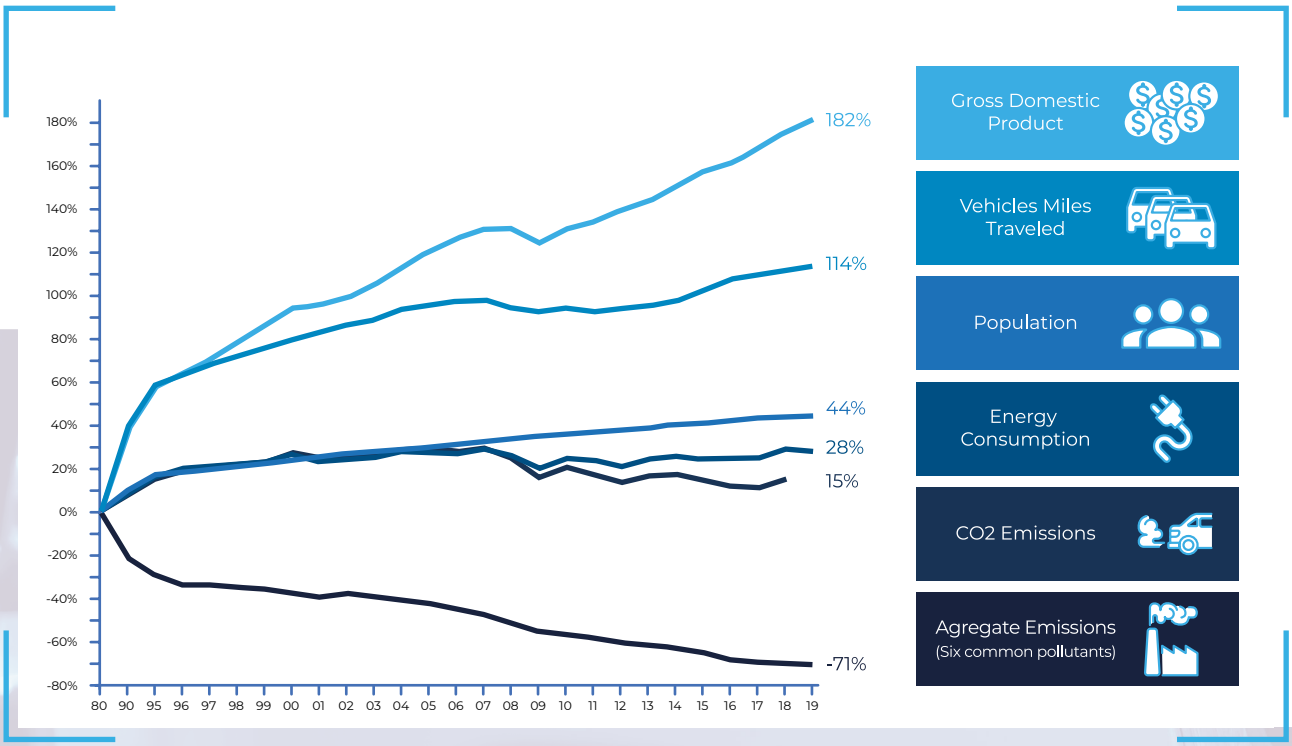
In fact, transportation has been always a huge generator of pollutant elements that are sent to the atmosphere at a fast rate. However, in order to control this huge impact, the authorities have set up more and more strict regulations with the aim of controlling that to the limit and pushing technology to generate cleaner engines.

[1] *For EPA standards on Heavy Duty, you can check* click here

And for non-road engines you can check click here

In the US, the regulations come from the Environmental Protection Agency (EPA). This authority's main goal is to care for the environment, and for this, the EPA has determined certain standards that engine manufacturers must meet. These vary from one type of vehicle to another and are updated periodically.

In the graph below, we can see how over the last 40 years, despite the exponential growth of the GDP (Gross Domestic Product), the growing population and the increase of both energy consumption and vehicle miles traveled, emissions of $C0_2$ and other common pollutants have been controlled to be tied to the lower percentage possible.



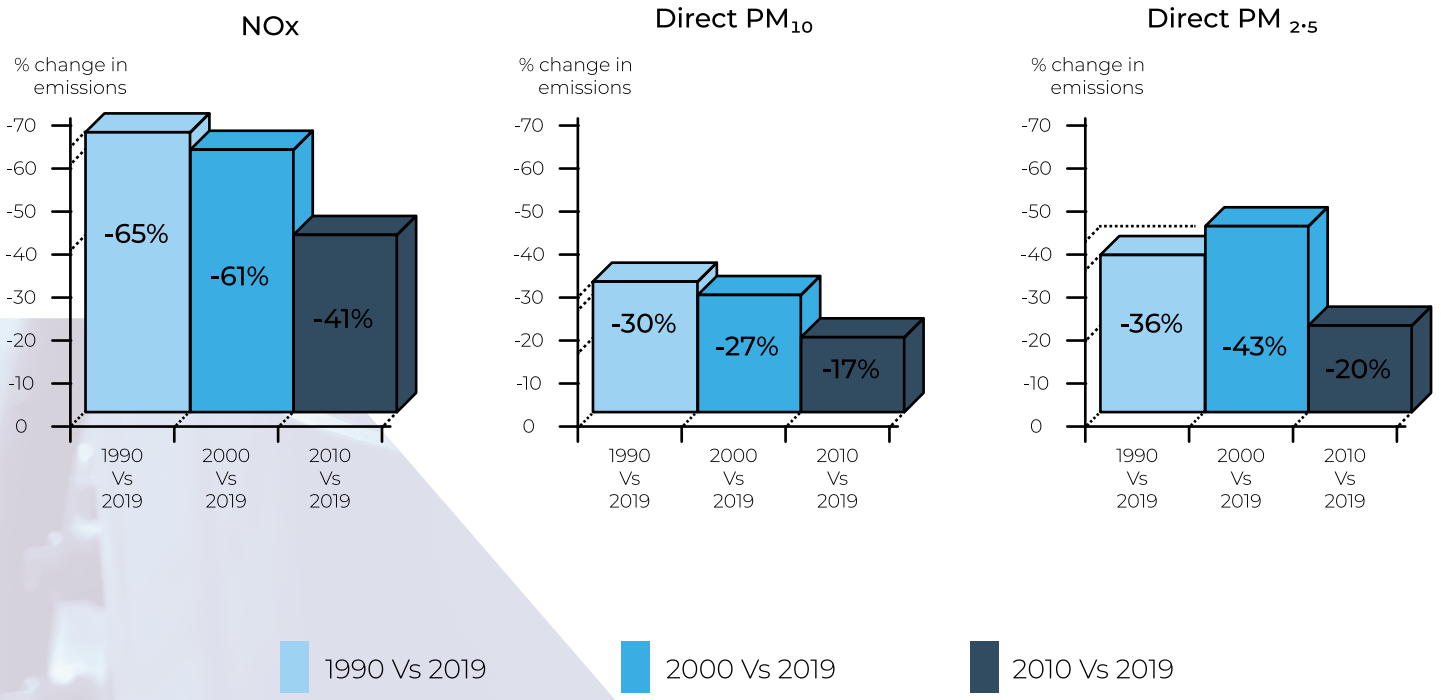
A comparison of sources of emissions and GDP growth, from 1980 to 2019. Source: EPA.

Furthermore, apart from regulations, technology has been also the gear towards the cut on emissions. In the following graphs, we see the percentage of reduction in the last 30 years as technology has made machines more efficient. These have been reached in part thanks to the development of different mechanisms like the Aftertreatment System.

"Just considering the period between 2010 and 2019, NOx emissions have been reduced over 40%."

Emissions trend graph: click here

% CHANGE IN EMISSIONS



Compared percent change in emissions over the past 3 decades. Source: EPA.

Truck industry and the impact on the environment

According to Josh Miller, researcher at the International Council on Clean Transportation (ICCT) "Heavy-duty vehicles—commercial trucks and buses—were by far the largest contributors worldwide, accounting for %76 of the total excess NOx emissions". The US is actually among the 5 markets[2] that contribute the most on NOx production toping altogether %90 of emissions in that category.

But why are now focusing particularly over NOx? Well, NOx is generated on every combustion and combustion is actually the driver of the engine. Every time diesel is burnt inside the engine, Nitrogen is generated. This element gets along perfectly with the Oxygen present in the air and join forces. This combination ends up becoming a very irritant gas that is what we call NOx (Nitrogen + Oxygen). This composition makes its way through the exhaust and is released into the atmosphere. Once it reaches the atmosphere, NOx reacts with sunlight and produces Ozone (O3), another unhealthy pollutant. The accumulation of this in busy areas is what causes that brownish smog that cover some major cities mostly in hot days.

"DID YOU KNOW... Today's diesel trucks emit 50x less NOx than comparable trucks from the 1980s?"

All these elements that are combined in the air we breathe have very harmful effects on our health and the environment. In fact, it is estimated that 1,100 deaths were caused from excess diesel NOx in 2015 for the United States where heavy-duty diesel vehicles caused 10 times the impact of light-duty diesel cars[3]. It makes sense, with a vast territory to deliver goods and a fragile railway system, diesel trucks are king.

To tackle this massive public health and environmental issue, there are all kind of mechanisms aiming towards the reduction of emissions thrown into the air. Technological developments along with targeted legislation are strategically helping in this attempt to reduce the NOx impact. New vehicles must meet the strictest of standards and different mechanisms has been put in place in order to cut down the emissions.

[2] *The other markets are Brazil, China, India and the EU.*

[3] *According to the study "Impacts and mitigation of excess diesel NOx emissions in 11 major vehicle markets", published in May, 2017.*

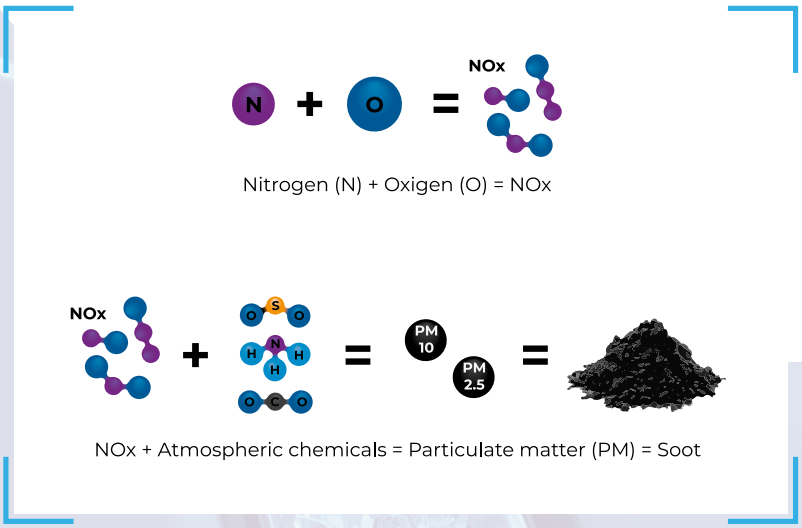


Diagram on how NOx and PM are generated.

II. Main pollutant elements: NOx and PM

Nitrogen (N) and oxygen (O) are present separately in the ambient air and by themselves can be harmless. Consequently, both elements are present in the air-fuel mixture that is combusted inside of the engine. Knowing this, it is easy to see that it would be impossible to design an internal combustion engine that does not produce NOx when it burns fuel.

"No internal combustion engine can exist without producing some amount of NOx"

The amount of NOx created during combustion varies with peak combustion temperature. The higher the temperature, the more NOx generated, thus the reason the EGR was created.

Once the NOx is generated, it reacts with atmospheric chemicals originating SOOT, also called particulate matter (PM). This is what blackens the smoke that goes out the exhaust.

In recent years, the amount of NOx and PM liberated to the atmosphere have seen a huge reduction.

Taking this into account, while electric alternatives are gaining ground slowly but surely, when it comes to heavy duty, the industry has leaned on technology in order to reduce NOx to its very limit, which is actually what we are going to cover over this white paper.

Before 2007

- **NOx emissions:** 2g/bhp-hr
- **Particulate matter emmisions:** 0.1g/bhp-hr

2007 and after

- **NOx emissions:** 0.2g/bhp-hr
- **Particulate matter emissions:** 0.01g/bhp-hr

% Reduction

NOx emissions: -90% (1/10)

Particulate matter emissions: -90% (1/10)

In the configuration of newer vehicles, there are many efforts devoted to the reduction of the total amount of NOx and PM generated as well as to the removal of NOx from the exhaust.

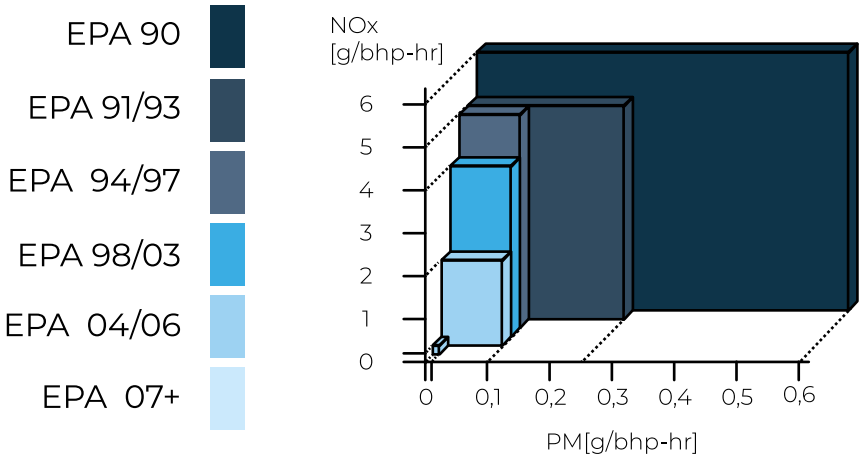
Some answers to this issue have been high-pressure common rail fuel injection systems, electronically controlled injector solenoids, and advanced turbocharging.

With that said, as technology has taken a lead role in the development of engines, legislation took control of the range. Little by little the reduction started taking place and kept going to current levels where the value is more than 50 times less than before.

In the following section we will see how the EPA has set different standards for Highway and Off Highway vehicles.

NOx and PM reductions for Heavy Duty Highway engines

Back in 1985, EPA started to determine the maximum NOx amounts that were allowed to be exhausted to the air. In 1989, PM were also added to the regulation list. Since then, the limitations have been set to meet stricter parameters. In the graph on the right we can see the evolution of g/bhp-hr of NOx and PM permitted over time until today. In the following graph we can see the enormous emission's decline that newer engines must meet.

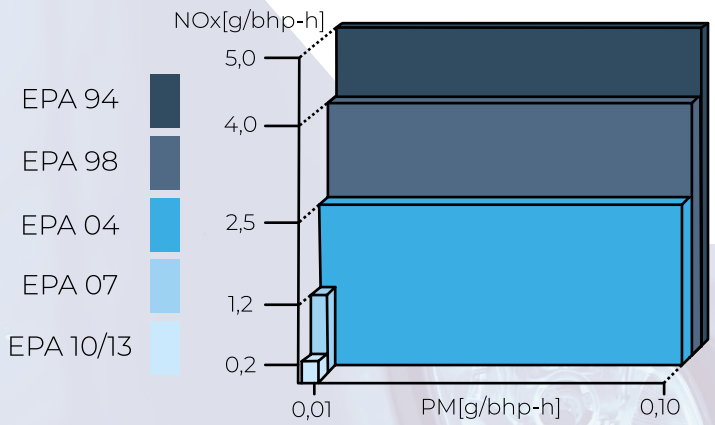


On Highway allowed NOx and PM emissions according to the different EPA standards. Source: EPA.

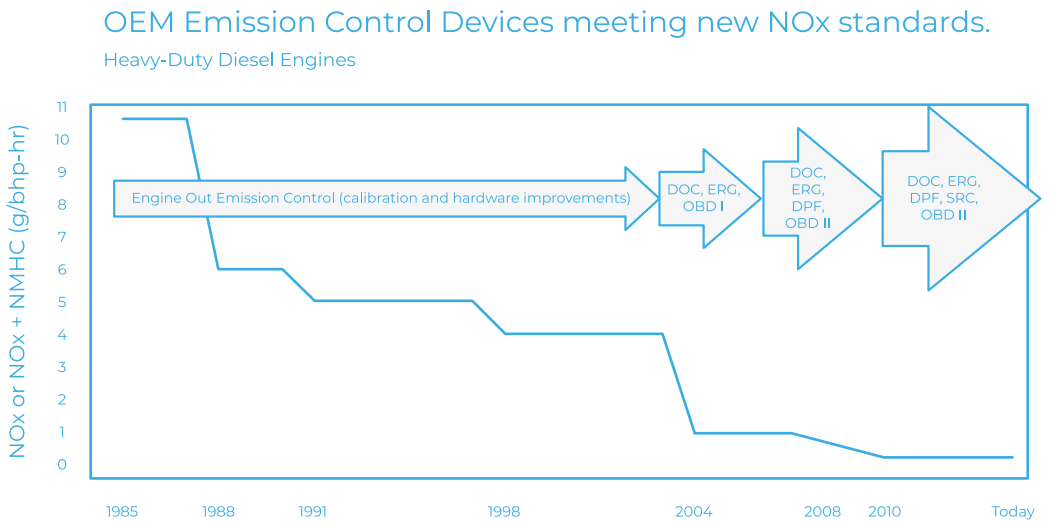
NOx and PM reductions for Off Highway engines

For Off highway engines, EPA distinguishes 4 tiers. By 2015, when final Tier 4 regulations were fully applicable, PM and NOx emissions had been reduced 99% compared to 1996 levels. From 2019, Tier 5 adds even stricter limitations. After Tier 4 Final, Tier 5's aim is reducing these harmful emissions to zero making emphasis on eliminating very fine particle of soot. On the technological side, there aren't many expectations on what manufacturers will deliver over 2020 when this new level of restrictions could be enforced.

"In a 20-year period, Off Highway's NOx and PM emissions have seen a cut of 99%. This is to say, a 1995 excavator emitted 99 times more of these than one in 2016."



Off Highway allowed NOx and PM emissions according to the different EPA standards. Source: EPA.



Data source: click here

As we see from data, the production capabilities of Original Equipment Manufacturers (OEM) have been over time heavily impacted by these strict emissions limitations. In part, these restrictions pushed the evolution of diesel engines and the development of resourceful mechanisms to reduce to the extreme the contaminant particles sent out to the atmosphere.

The chart above shows how OEMs adapted to the changes and developed different solutions in order to meet the EPA standards. Initially, calibration and hardware improvements got along. Further in time, DOC, EGR and OBD I were added as effective measures to limit the amount of harmful emissions being spread out. After a few years, OBD I turned into OBD II allowing simple plug-in test that would only take seconds to be performed plus more emissions problems detected thanks to its broader communication capabilities.

Finally, EGR was introduced to help constrain emissions to the limit meeting 2007 new standards. As DOC, EGR, DPF, SCR and OBD II became standard these have been gradually implemented on heavy duty diesel engines.

III. Aftertreatment system and the cut on emissions

For the purpose of delivering cleaner exhaust and meeting environmental standards Diesel Particulate Filters (DPFs) were introduced to diesel engines in the year 2007.

"Did you know Caterpillar struggled to meet EPA standard for On-Highway engines? They left this market in 2007 since they find it very difficult to keep meeting the changing standards."

However, there is more than a filter in the exhaust system. The whole aftertreatment system of the vehicle has made possible the achievement pointed out by EPA who states that new heavy-duty trucks and buses are roughly 99 percent cleaner than 1970 models.

The original purpose of the exhaust system was to route exhaust gases from the engine in a safe manner getting them directed to the environment, while also providing the reduction of combustion noise.

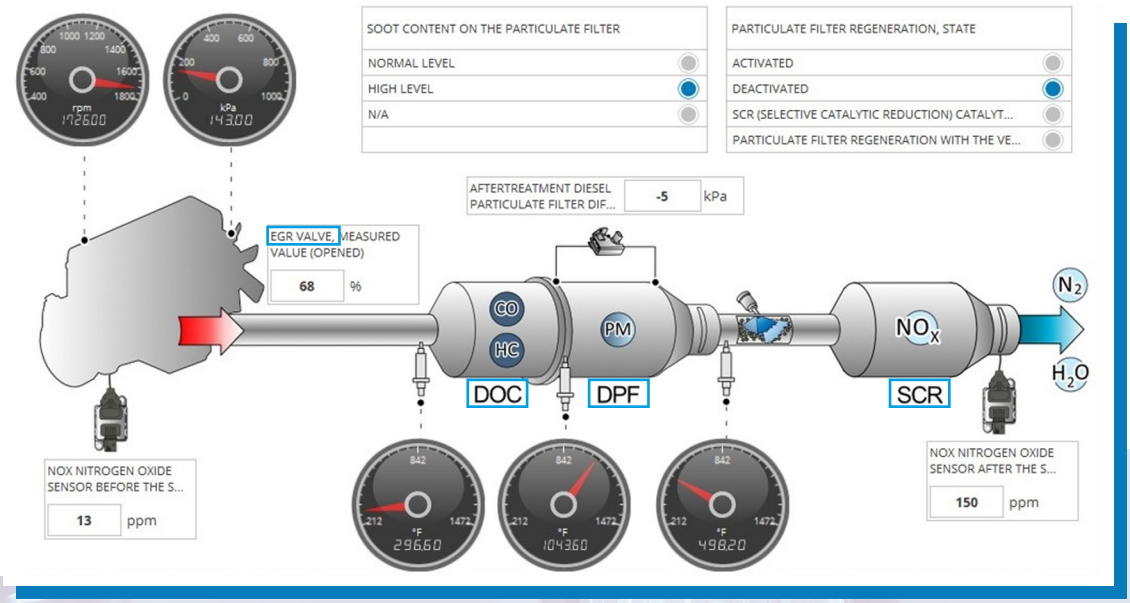
However, over time, increasing concern on public health issues would emphasize the harmful components that this process was sending straight out to the atmosphere and that we have learnt about in the previous sections.

To tackle this situation other responses were created. This is how the idea of treating those gases inside of the vehicle before they exit to the atmosphere came about, and this is in fact how the aftertreatment systems came to life.

Aftertreatment breakdown

In the exhaust, we find an array of systems whose main purpose is the treatment of post-combustion gases after they leave the engine. This allows considerable reduction of environmental impact without sacrificing power or performance that are "a given" on a vehicle meant to perform a heavy-duty job.

These systems can be broken down into the following components: **EGR, DPF, DOC** and **SCR**.



Preview on how the Aftertreatment is usually laid out: parts and sensors. Source: Jaltest Software.

Exhaust Gas Recirculation (EGR)

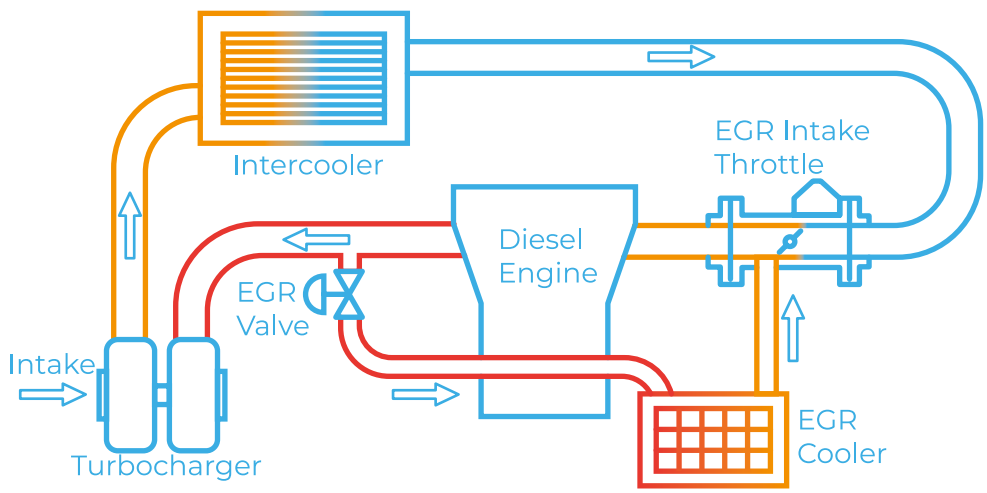
Heat is one of the main drivers of NOx generation. The EGR system works on regulating the temperature inside of the system. A small amount of cooled exhaust gas is sent back into the combustion chamber. As the temperature in the chamber lowers, the production of NOx is reduced.

However, in this process, particulate emissions increase. This is a reason why EGR is not sufficient to meet the strict standards, it fixes one issue but increases the other.

Diesel Oxidation Catalyst (DOC)

The DOC reduces particulate matter and oxidizes carbon monoxide and hydrocarbons.

The DOC is the first step in the aftertreatment funnel. It is a filter that contains precious metals that works on the oxidation of hydrocarbons, carbon monoxide and unburned fuel and oil. The gases pass through the filter. Both the DOC and the DPF are made of honeycomb ceramic filters that allow the flow of air to be laminar and better managed.



This image depicts how the EGR system functions. Exhaust gases exit the exhaust manifold through the EGR valve, then enter the EGR cooler to reduce the gas temperature. Once cooled, the gasses ente a crossover pipe where they are mixed in with the fresh air charge to reenter the engine cylinders.

Diesel Particulate Filter (DPF)

The DPF systems main purpose is reducing the particulate count. This filter itself is designed to remove more than 90 percent of particulates out of the exhaust, according to Raymond Parrish, a Service Engineer at Cummins.

The DPF is a filter that will trap any remaining soot that the DOC couldn't oxidize. The soot or PM will remain in the DPF until a regeneration is undergone, either passively or actively. While an active regeneration of the DPF takes place, the vehicle's situation is that of driving down the road. However, there are some conditions that must meet. For example, certain length in a straight line or a given amount of time at a certain speed. On the other hand, the passive regeneration is carried out in the shop, with the truck stopped, when maintenance actions or repairs are being carried out. In today's vehicles, these types of actions can only be carried out by top level diagnostics tools that have the electronics capable of reading and executing said action.

You will learn more about the details of regeneration on Part II of this White Paper. click here

Selective Catalytic Reduction systems (SCR)

This catalyst reduces the amount of nitrogen oxide (NOx). The whole SCR is composed by the following elements:

A **Diesel Exhaust Fluid (DEF)** – A solution made of urea and deionized water. This liquid is introduced into the exhaust stream to reduce NOx emissions. It is dense and it can crystalize due to temperature changes, making it a key element in the maintenance of the aftertreatment system.

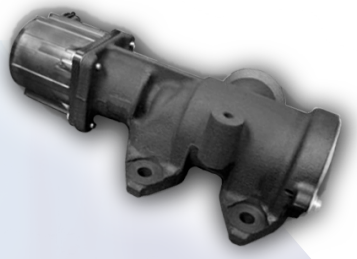
B **DEF pump** – A part of the DEF delivery system that vacuums DEF from the tank through the pump. It then filters the DEF and maintains pressure between the DEF pump and the DEF doser. When issues arise in the DEF Pump, you always have the resource of launching a DEF pressure test. With stated action, the system pushes air into the system making all the DEF Fluid recycle throughout the setup.

C **DEF doser** – The doser applies DEF into the exhaust system in order to generate the gaseous transformation. It sometimes gets clogged or limited due to crystallization. By carrying out a DEF Doser Test the liquid gets pushed to measure the actual amount of DEF that is entering the system.

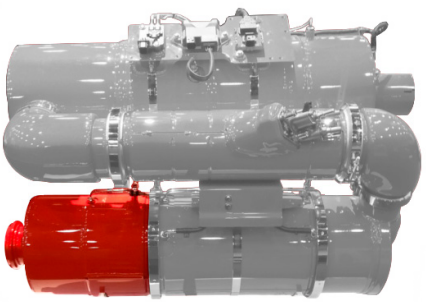
"SCR systems on new technology diesel trucks eliminate emissions while reducing fuel consumption."

D **Decomposition chamber** – This where the DEF is mixed with the exhaust gas stream before this reaches the SCR.

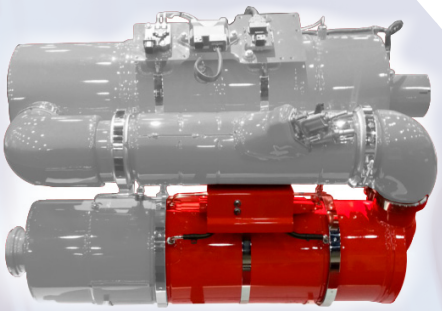
E **SCR** – This is the catalyst where the chemical reaction that transforms the combination of the exhaust stream and decomposed DEF takes place. This is the way how NOx is cut down to meet the set standards. Here the DEF is contributing to the breakdown of NOx that passes through the SCR. At the end of this step there is a NOx sensor that measures the NOx levels that are resultant. The importance of the NOx sensors is the depreciation value, meaning, the value is irrelevant by itself, the value is measuring what goes into the chamber and making sure that what goes out is less in quantity. Sometimes, the NOx sensor is what identifies the fault but is not the cause, and swapping a sensor makes no sense, but going up through the process above is the key to perform a solid diagnostics analysis and an efficient solution.



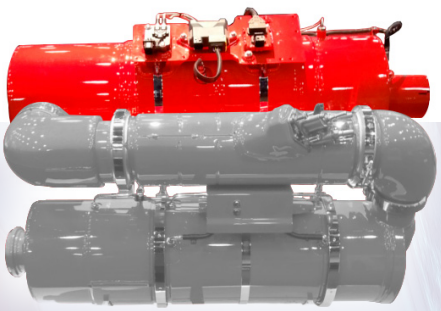
EGR



DOC



DPF



SCR

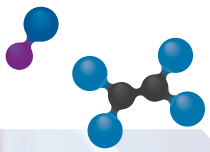
As the DOC and DPF have worked together during the process, carbon monoxide and hydrocarbons are reduced, and soot and ash of the exhaust system have been also diminished. Ultimately, with the addition of DEF to the mix, it is possible to liberate cleaner exhaust to the atmosphere. That resulting 'exhaust' is made up of harmless nitrogen gas and water vapor.

In addition to the primary components of the aftertreatment system, there are also sensors positioned throughout all the system. Jaltest Diagnostics, the all-makes and all-system solution, is able to monitor the performance of all these while any maintenance action is taking place. This real time analysis breakdown is also stored on a report that can be checked later on, filed for future vehicle interventions, and also shared with the customers for a detailed analysis of the functions carried out.

A differential pressure sensor estimates captured particles in the DPF. There are also several exhaust gas temperature sensors monitoring temperatures throughout the system. On the other side, the NOx sensors measure the quantity of this element both before and after the chemical reaction triggered by the DEF. And finally, there are particulate matter sensors, also known as soot sensors, that measure particulates in the exhaust (mainly ash and soot).

"Sensors are often great indicators of pending repairs and maintenance and will point out any issues that the aftertreatment system may be facing."

THE COMBINED FUNCTIONING OF DOC AND DPF



Carbon monoxide, hydrocarbons

↓

REDUCED

Soot and ash

↓

DIMINISHED

Sensors in charge of tracking the whole process

↓

- **Exhaust gas temperature**
- **NOx sensors** (before and after the chemical reaction triggered by the DEF)
- **Particulate matter sensors = soot sensors**

IV. Stages of aftertreatment system's issues

In general, there are 5 different stages of aftertreatment issues, going from a lax warning and a light on to a power restriction and putting the vehicle on limp mode.

A warning light usually shows up indicating it is time for a regeneration as a burn out of the accumulated soot is already needed. If we faced a clogged filter, the vehicle's reaction would be different, to the point that power issues of major consideration may arise. In any case, the best behavior is anticipation and it is also recommended to follow a good maintenance schedule.

It is important to understand that not every level of warning is the same as well as the differences in what you are eliminating in each of the steps, for example, the detailed function of the DPF vs. the SCR.

In the graph below we can see the different stages with their recommended actions. In the first stages, while the filter is getting full but there is still room for more accumulation, it is going to be the vehicle by itself who will prompt a regeneration, on its own while the vehicle is driving. The only thing that the driver may notice is that the aftertreatment warning lamp will flicker on the dashboard.

Once the level of ash is so high that the filter is getting clogged, the vehicle will experience a loss of power and eventually will go on limp mode. That is what correspond with stages 4 and 5 of the illustration.

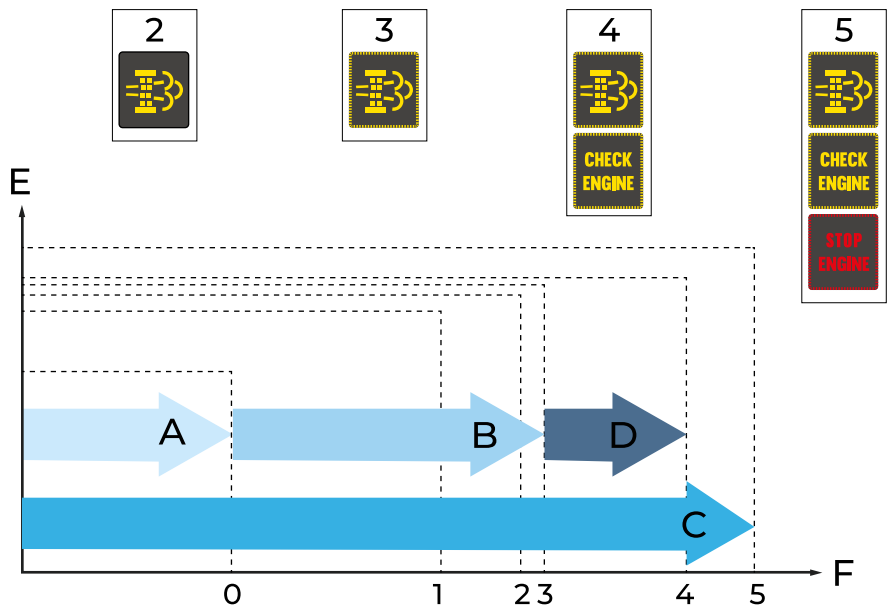
It is of great importance to try and tackle these situations before you reach stages 4 and 5 because at this point the engine will begin to restrict its power output to protect itself. Causing reductions to 35 mph first and then taking you to the very undesirable limp mode at 5 mph.

Actions

A - Passive regeneration.
B - Active regeneration.
C - Stationary regeneration.
D - Power loss 25%.
E - Ash level.
F - Procedure approximate time.

Lamp behavior

2 - Signal permanently activated.
3 - The image flickers on the display screen.
4 - The image flickers on the display screen.
5 - The image flickers on the display screen.



Stages of aftertreatment system›s issues. Source: Jaltest Software.

Did you know that...

A proper maintenance schedule of the aftertreatment systems can result in thousands of dollars of savings a year per truck. How do we do that? Don't miss out on the next take of this white paper where all the details on how to maintain the aftertreatment system with Jaltest Diagnostics in order to increase uptime and save thousands.

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