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Homologation process of an Euro VIe heavy-duty diesel engine

Supervisor:
Prof. Ezio Spessa

Tutor:
Dott. Mattia Bientinesi

Candidate:
Giuseppe Testa

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Abstract

This thesis work, carried out in cooperation with FPT Industrial, focuses on the description of the homologation process of a new diesel engine for heavy-duty on-road applications, in compliance with the EURO VI step E emission regulation.

After an overview of the main pollutants that affect human health and the environment, the emission legislative framework of the most important world market regions will be presented, with a focus on EMEA and NAFTA. It follows a detailed description of the EU pollutant emission standards for heavy-duty vehicles, together with the next emissions targets in terms of CO_2.

The respect of the current norms has been granted by an high technological content provided on the engine project and the calibration effort, without neglecting the innovative strategies and layout developed for the after-treatment system. These refined product characteristics are the result of the product development process adopted by FPT Industrial, which has as its main objective the full satisfaction of the customer’s requests and the leverage on improvement and innovation.

The homologation process for HD engines requires the execution of specific dyno tests (WHSC, WHTC, and WNTE) as well as road tests performed in real driving conditions on a reference vehicle. The latter are performed using the PEMS equipment, and they are required both for type approval and in-Service conformity (ISC). Conformity of Production tests (CoP) are performed after the engine launch on the market, and they are used to monitor its emission performances.

Going further to the homologation requirements, when a new product enters the market, there is a need to find a procedure that ensures customer satisfaction, stability of production, and performance in the immediate post-launch phase. For this purpose, The Early Warning Team process and the tutorship program, aimed at analyzing and solving promptly the quality issues relating to the launch of a new engine, have been examined.

1. Introduction

1.1 Worldwide emissions overview

Burning fossil fuels is commonly recognized as one of the main influencing factors of the climate and the Earth's temperature. It gives a consistent amount of greenhouse gases to those naturally occurring in the atmosphere, increasing the greenhouse effect and global warming.

2011 - 2020 was the warmest decade recorded, with global average temperature reaching 1.1°C above pre-industrial levels in 2019. Human-induced global warming is currently increasing at a rate of 0.2°C per decade. An increase of 2°C compared to the temperature in pre-industrial times is associated with serious negative impacts on the natural environment and human health, including a much higher risk that dangerous and catastrophic changes in the global environment will occur. For this reason, the international community has recognized the need to keep the warming well below 2°C and pursue efforts to limit this value to 1.5°C.

In the following picture, the temperature trend in the next 100 years is shown, according to four different emission scenarios.

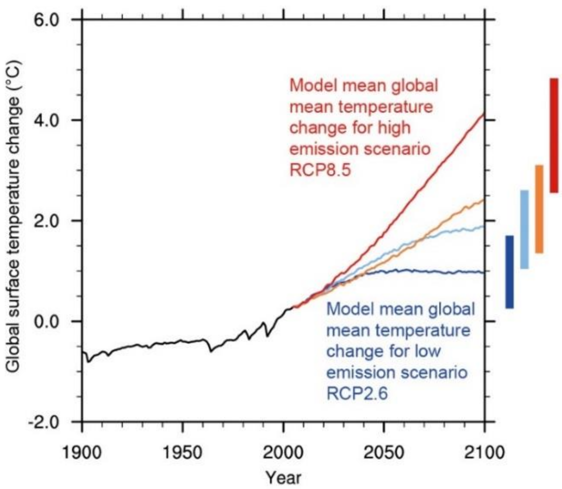

FIGURE 1.1 – TEMPERATURE TREND

The main driver of climate change is the greenhouse effect. Some of the gases existing in the Earth's atmosphere act like the glass in a greenhouse, trapping the sun's heat and stopping it from leaking back into space. This is the main cause of global warming [1].

Many of these gases occur naturally, but the human activities are contributing to increase the concentration of some of them in the atmosphere, in particular:

- Carbon dioxide (CO_2)
- Methane (CH_4)
- Carbon monoxide (CO)
- Sulphur dioxide (SO_2)
- Nitrogen oxides (NOx)
- Fluorinated gases
- Ozone (O_3)
- Aromatic Polycyclic hydrocarbons (PAHs)
- Dusts (PM particles within 10 μm of diameter)

A deeper overview of the main pollutants is proposed below.

The CO_2 produced by anthropogenic activities is the largest contributor to global warming. By 2020, its concentration in the atmosphere had risen to 48% above its pre-industrial level (before 1750). It is not considered a proper pollutant, but it has the capability of retaining the sun radiation, contributing to the temperature increase.

In the same family, i.e. that of the climate warmer, there is certainly Methane (CH_4). It is a powerful greenhouse gas and short-lived climate pollutant. It promotes the formation of ozone at ground level and particulate, which is very harmful for humans. Oil and gas, agriculture and landfills are major sources of this powerful pollutant [5].

Carbon monoxide (CO) is a colorless and odorless gas. It is emitted by several combustion sources, including internal combustion engines, power plants, wildfires and it is caused by the incomplete combustion of carbon containing fuels like natural gas, gasoline, or wood. CO indirectly contributes to global warming because it promotes the formation of ozone in atmospheric chemical reactions. Inhaling carbon monoxide is a risk for human health because it decreases the blood’s capacity to deliver oxygen throughout the body [2].

Sulphur dioxide (SO_2) is an hazardous air pollutant, occurring naturally or by human activities. It is emitted mainly due to petroleum refinement and wood pulping, but it can occur also in the exhaust fumes produced by vehicles. When this gas is released in the atmosphere it can harm plants, marine life, water bodies, and the soil. When it moves into the air it dissolves into the water to form sulfuric acid, which results in acid rain [3].

The term nitrogen oxides (NO_x) encompass a mixture of nitric oxide (NO) and nitrogen dioxide (NO_2), which are gases produced from natural sources, motor vehicles and fuel burning processes. NO is colorless and odorless and is oxidized in the atmosphere to form NO_2. Nitrogen dioxide has an odor, is an acidic and highly corrosive gas that affects human health and the environment. Elevated levels of NO_2 may cause damage to the human respiratory tract, resulting in respiratory infections and asthma. For the environment it is harmful to the vegetation, damaging foliage. It reacts with surfaces fading and discoloring furnishings, and it causes reduction of visibility. In general nitrogen oxides are critical components of photochemical smog [4].

Fluorinated gases are gases of anthropogenic origin that are used in several industrial applications. They entered into force to replace the substances that were considered harmful for the atmospheric ozone. Nevertheless, they are also powerful greenhouse gases, even more than CO_2. Hydrofluorocarbons (HFC) are included in this category [6].

Ozone (O_3) at atmospheric level is very important for the ecosystem because it reflects the sun’s ultraviolet rays. Ground level ozone, by the way, is harmful for humans because it damages airways, aggravates lung diseases, asthma, and heightens stroke risk [12].

Polycyclic aromatic hydrocarbons (PAHs) are widespread across the world, and they are very persistent in the environment. These compounds can be consumed by humans mainly by inhalation, dermal touch, and ingestion. They are considered very dangerous for humans because, under long exposure, they promote the onset of tumors. The anthropogenic sources of emission are industrial, mobile, domestic, and agricultural. Exhaust smoke coming from diesel and gasoline engines is also accounted [7].

Another dangerous family of pollutants is certainly particulate matter (PM, also known as particle pollution). The term refers to the mixture of solid particles and liquid droplets found in the air. Some particles, such as dust, dirt, soot, or smoke are large or dark enough to be seen with the naked eye. Others can be only detected using the microscope. Particle pollution includes:

- PM_{10} : inhalable particles, with diameter of 10 µm and smaller;
- $PM_{2.5}$: fine inhalable particles, with diameter 2.5 µm and smaller.

These particles come in different sizes and shapes and can be made up of hundreds of different chemicals. Most of them form in the atmosphere as result of complex reactions of chemicals such as sulfur dioxide and nitrogen oxide, which are emitted from power plants, industries, and vehicles. Particulate matter contains liquid or solid droplets that are so small that can be inhaled, causing serious health problems. Some particles, with diameter less than 10 µm can get deep into lungs and some may even reach the bloodstream. Concerning the propulsion technology of heavy-duty vehicles, PM10 is mainly produced by diesel engines.

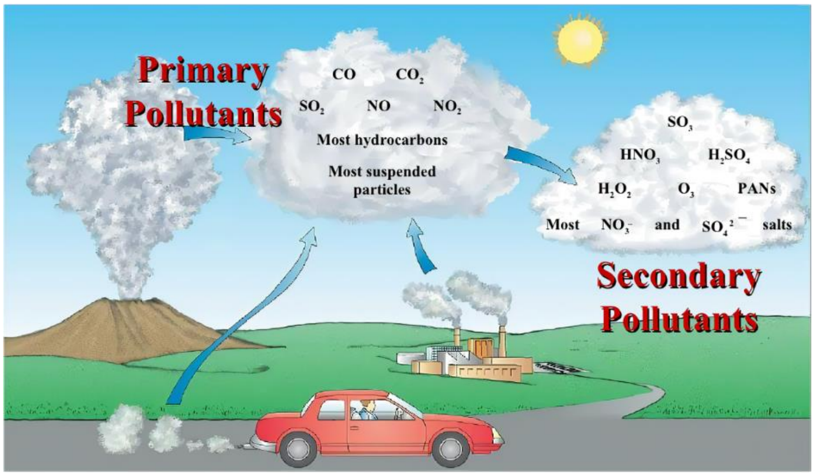

FIGURE 1.2 - CLASSIFICATION OF POLLUTANTS

Sulphur dioxide, nitrogen oxides, carbon monoxide and dioxide, and particulate matter are called primary pollutants. This is because, independently whether they come from natural or anthropogenic sources, they are directly emitted into the atmosphere. The secondary pollutants result from the chemical reactions or physical interactions between the primary ones themselves or between the primary pollutants and other atmospheric components [9].

Cars, trucks, and buses powered by fossil fuels are major contributors to air pollution. In fact, transportation emits more than half nitrogen oxides in the air and is a major source of heat-trapping emissions. American studies have linked pollutants from vehicle exhaust to adverse impacts on human bodies, on nearly every organ system in the body. This problem is felt especially in the big urban conglomerates, where there are a lot of vehicles, and people are exposed to higher level of air pollution.

Trucks and buses play a major role in our lives, hauling goods from manufacturer to stores, picking up the trash, delivering packages and transporting thousands of people around cities, every day. But these vehicles also greatly affect public health and global warming.

Heavy-duty vehicles (HDV) comprise only about 10% of all vehicles on the road, yet they generate more than 25% of global warming emissions, 45% of NOx emissions, and nearly 60% of direct $PM_{2.5}$ emissions from on-road vehicles that come from transport sector [8].

Light-duty and Heavy-duty vehicles can be considered one of the most important causes of world pollution. The European Community considers that, being 100 the total amount of CO_2 emissions coming from road transport, the majority is attributable to passenger cars and light-duty commercial vehicles. The remaining 25-30%, instead, comes from heavy-duty trucks and buses.

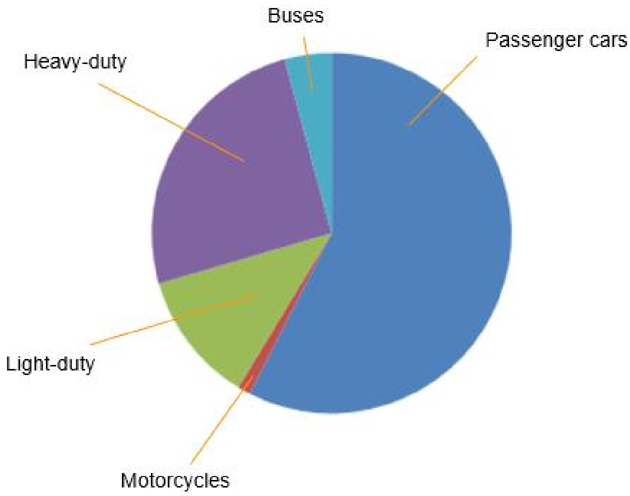

FIGURE 1.3 - TOTAL CO2 EMISSIONS OF ROAD TRANSPORT

CO_2 emissions are only a partial view on the pollutants that these kinds of vehicles produce every day in the world. Commercial vehicles, due to their exhaust gases, are the reason for the high concentration of CO (Carbon monoxide) in many European towns, and for the high concentration of NO_2 (Nitrogen dioxide), especially in the big towns of North America.

This problem has risen over the years, and this has forced the environmental agencies to start adopting measures, with the aim of containing the environmental impact of road transport. For this reason, governments around the world have established standards on engine emissions to control and reduce the harmful pollutants emitted by vehicles and machinery.

These standards have played a crucial role in reducing air pollution and protecting the environment. They are regulations that dictate the maximum amount of pollutants that can be emitted by vehicles and other combustion engines.

By implementing these standards, governments aim to improve:

- Air quality;
- Mitigate the harmful effects of vehicle emissions on human health;
- Lowering Greenhouse gases emissions (GHG);
- Moving towards more sustainable fuels.

Many efforts have been conducted by environmental entities and international authorities to try to involve as many countries as possible in taking note of environmental issues.

It is well known the Paris agreement, which is a legally binding international treaty on climate change. It was adopted by 196 Parties at the UN Climate Change Conference (COP21) in Paris, France, on 12 December 2015. It set that participant countries had to pursue effort in limiting the increase in the global average temperature to 1.5 degrees above pre-industrial levels. To reach the goal, the greenhouse gas emission must have peaked before 2025 at the latest and decline by 43% by 2030.

More recently, there was the COP28 UN Climate Change Conference of Dubai, that was held on December 2023. With about 85'000 participants and more than 150 Heads of State and Government, it was the biggest conference of its kind. It was important because it marked the conclusion of the first "global stock take" of the world's effort to address climate change under the Paris Agreement. The words were not encouraging, because it was stated that progress was too slow across all areas of climate action [10].

Unless greenhouse gas emissions fall dramatically, warming could pass 2.9 °C this century, which would have not good consequences for life on this planet. Climate change, together with biodiversity loss and increasing pollution, are three interconnected crises that are putting economic and social well-being at risk. That's why it is so important to have strong regulation and centralized action by the governments of the macro areas of the planet [11].

1.2 Geographical market segmentation

The emission standards are different according to each country's policy. Vehicles that are sold in North America, Canada and Mexico are intended to be sold in the NAFTA market. NAFTA is an acronym that stands for North America Free Trade Agreement. It was a free trade agreement between United States, Canada and Mexico and modeled on the already existing free trade agreement between Canada and the United States (FTA), in turn inspired by the European model.

The agreement was stipulated among the three involved governments on 17th December 1992 and entered into force the 1st January 1994. The vehicles sold in the NAFTA market must respect the emission regulations made by the United States Environmental Protection Agency (EPA). EPA is an independent agency of the United States government that deals with environmental protection matters. It also monitors and ensures the respect of the emission standards for vehicles.

FIGURE 1.4 - NAFTA COUNTRIES

North America based companies often divide their international operations into the following regions:

- Northern, Central and South America (NCSA, AMER, AMS, NALA);
- North America, being Canada, United States and Mexico (NORAM);
- Latin America and the Caribbean (LATAM, or LAC);
- Asia Pacific and Japan (AP, APAC, JAPA or APJ or JAPAC);
- India, Middle East, and Africa (IMEA)

Another important acronym is EMEA, which is the abbreviation for Europe, Middle East, and Africa. EMEA is a geographical designation used in the economic and business field. There are also two variants: SEMEA (South Europe, Middle East, and Africa) which exclude Northern Europe countries and MEMEA (Mainland Europe, Middle East, and Africa) which exclude the British Islands.

The market of destination, i.e. the market where the vehicle is sold, is very important for OEMs because manufacturers must respect the rules imposed by the local commissions. For instance, the passenger vehicles sold in EMEA region must respect the emission standards defined by the European Commission (like Euro 1, 2, 3, 4, 5, 6).

The European commission is one of the main institutions of the European Union. It represents and protects the interests of the European Union like economy, policies, environment. Having the monopoly on the power of legislative initiative, it proposes the adoption of EU regulatory acts [13].

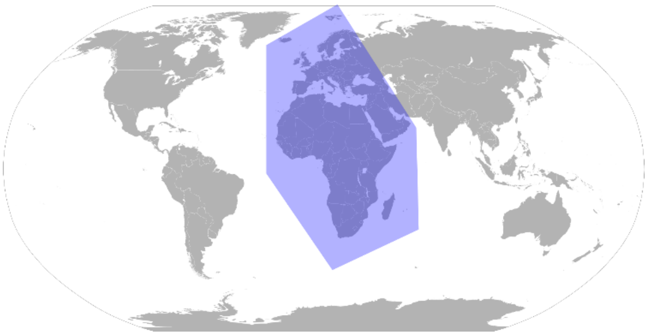

FIGURE 1.5 - EMEA COUNTRIES

1.3 On road heavy duty vehicles standard emissions

In road transport the search for new technologies and fuels has been driven by regulators, which have been mandating increasingly stringent standards for emissions of air pollutants, fuel economy and ability to use alternative fuels.

The air quality deterioration caused by the road traffic has kept under attention and monitored since the end of the ‘60s, at least in the three main areas where the economic growth was accompanied by a growth in the number of vehicles on the road: North America, Europe, and Japan.

The emissions of pollutants and GHG gases from vehicles are closely related to the operating conditions of the engine. To verify the compliance with approvals, the emission standards provide some tests. The objectives of emission test procedures are:

- to reproduce in a controlled and repetitive way, the statistically most frequent conditions of use of a powertrain, depending on its application;
- establish sampling systems and instrumentation to be used to measure with accuracy and precision the amount of pollutants emitted.

The development of these procedures involved both the authorities responsible of the environment protection, and industry. International panels of experts from different countries have also been involved in the process to promote the harmonization of the test procedures.

The analysis carried out in this thesis work is focused on the legislative framework adopted in the European Union. In the following pages, an overview of the European standard emission for all vehicles will be given, with a focus on the heavy-duty vehicles and the current standard [12].

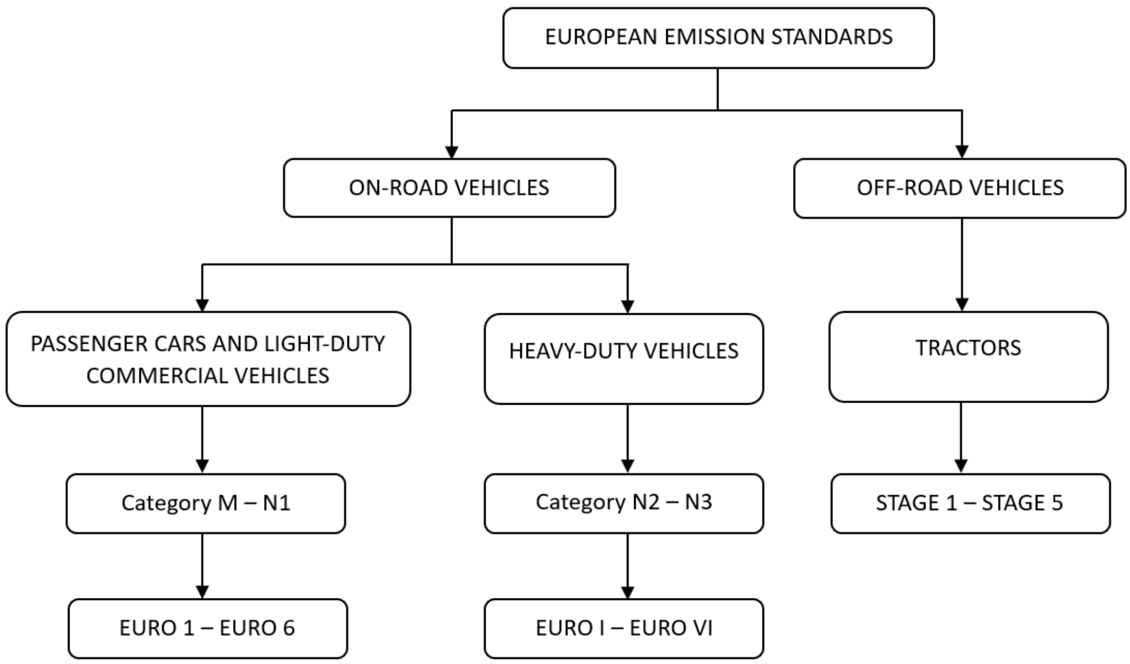

FIGURE 1.6 - EMISSION STANDARDS OVERVIEW

The European emission standards are vehicle emission standards for vehicles sold in the European union, the European economic area member states and the United Kingdom. The standards are defined in a series of European Union directives setting out the gradual introduction of increasingly strict standards.

The first emission standard for Heavy-Duty vehicles has been introduced in Europe in 1988. The "Euro" track was implemented starting from 1992 with the Tier Euro I, with increasingly severe standards released every few years.

The emission standards for trucks and buses are defined by the engine energy output, which is expressed in g/kWh. This is unlike the emission standards for passenger cars and light commercial vehicles, defined by vehicle driving distance in g/km.

For what the heavy-duty vehicles are concerned, the emission tests are performed only at the engine level, with its ATS (After Treatment System) on, but not on the whole vehicle (like passenger cars and light-duty commercial van).

The stages of the emission standards are referred using Roman numerals (Euro I, II, III, …, VI), unlike that for passenger vehicles and LDV that use Arabic one (Euro 1, 2, 3, …, 6). These tiers are introduced gradually by the European Commission whenever upgrades on emission limits are made.

When a certain stage enters into force, all vehicles manufacturers must end the sales of all vehicles compliant with the previous stage and they must introduce progressively on market vehicles respecting the new emission limits. This practice is known as "phase-in period", where the percentage of vehicles compliant with new regulation gradually rises [13].

The European Legislative framework provides a vehicles classification in categories, based on the vehicle main function and weight:

- Category M: motor vehicles with at least four wheels designed and constructed for the carriage of passengers. It comprises more sub-groups:
    - M1: vehicles designed and constructed for the carriage of passengers and comprising no more than eight seats in addition to the driver's seat;
    - M2: vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass ("technically permissible maximum mass") not exceeding 5 tons;

    - M3: vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver’s seat, and having a maximum mass exceeding 5 tons.
- Category N: motor vehicles with at least four wheels designed and constructed for the carriage of goods. It comprises more sub-groups:
    - N1: vehicles designed and constructed for the carriage of goods and having a maximum mass not exceeding 3.5 tons;
    - N2: vehicles designed and constructed for the carriage of goods and having a maximum mass exceeding 3.5 tons but not exceeding 12 tons;
    - N3: vehicles designed and constructed for the carriage of goods and having a maximum mass exceeding 12 tons [13].

There is also a specification about the term “mass”. There are four definitions:

- Maximum mass: gross vehicle mass (GVM), i.e. the maximum operating mass allocated to a vehicle based on its construction features and its design performance and declared by the manufacturer. It doesn’t include any trailers – gross combined mass is the term for that. Included in the GVM are the vehicles plus any fluids (fuel, brake fluid, water, etc.), accessories, driver passenger and any goods you are carrying in the vehicle. Therefore, a vehicle will have a dry weight (what it weighs on its own without fluids), a kerb weight (what it weighs on its own with all fluids at recommended levels and the fuel tank full) and a GVM. The gross vehicle mass minus the kerb weight and the weight of any passenger gives you the maximum weight of any cargo you can carry.
- Reference mass: mass of the vehicle in running order less the uniform mass of the driver of 75 kg and increased by a uniform mass of 100 kg.
- Mass in running order: the mass of the vehicle, with its fuel tank(s) filled at least 90 per cent of its or their capacity/capacities, including the mass of the driver and the liquids, fitted with the standard equipment in accordance with the manufacturer’s specifications and, where they are fitted, the mass of the bodywork, the cabin, the coupling, and the spare wheel(s) as well as the tools when they are fitted.

- Unladen mass: mass of the vehicle in running order without driver, passenger, or load, but with the fuel tank 90 per cent full and the usual set of tools and spare wheel on board, where applicable.

Light commercial vehicles belonging to the category N1 are further divided into three weight classes as shown in the following table. This classification is based on the Reference Mass [15].

CLASS	Reference Mass, RW	
	Euro 1-2	Euro 3+
I	**RW ≤ 1250 kg**	**RW ≤ 1305 kg**
II	**1250 kg < RW ≤ 1700 kg**	**1305 kg < RW ≤ 1760 kg**
III	**1700 kg < RW**	**1760 kg < RW**

TABLE 1.1 - WEIGHT CLASSES OF N1 VEHICLES

Hereafter an overview of the previous European Emission Standards for Heavy-Duty vehicles:

- Euro I: the standard was implemented in 1992. It was applied for both passenger cars and light trucks [13];
- Euro II: it was introduced in 1996 and it was applied to both truck engines and voluntarily for urban buses [13];
- Euro III: it was adopted by the EU in 1999. This directive also introduced Euro IV and V standards. In 2001, the European Commission adopted an amendment that prohibited the use of emission “defeat devices” and “irrational” emission control strategies. This directive would reduce the efficiency of emission control systems when vehicles operate under normal driving conditions to a level below those determined during the emission testing procedure [13].
- Euro IV and V: these standards were adopted respectively in 2005 and 2008. These standards introduced durability and on-board diagnostic (OBD) requirements. OBD is a device that can detect catalyst malfunctions that would

cause emissions to exceed the OBD threshold limits (OTL). The durability involves the ATS, for which a minimum duration has been established. The emission standards have been updated in 2005. It stated the new requirements for OBD durability and the new provisions for emission systems that use consumable reagents. When Euro IV and Euro V were adopted, regulators expected the stringent emission standards to require the use of DPFs (Diesel Particulate Filters) in commercial Heavy-Duty vehicles. However, by tuning their engines for high levels of NOx and fuel economy, and relatively low levels of PM emissions, manufacturers were able to comply with the Euro IV and V emission standards without the use of DPFs. These manufacturers used Selective Catalytic Reduction (SCR) to decrease tailpipe NOx emissions to meet Euro IV and Euro V standards. However, this compliance strategy did not reduce emissions of the smallest and most hazardous particles to the same degree as DPFs [13].

1.4 Euro VI Step E standard

The Euro VI, stage E, is the prevailing emission standard for Heavy-Duty vehicles in the European Union, which includes the European Commission, Parliament, Council, and Member States. This regulation applies to rigid and tractor trucks in categories N2 and N3, with axle configurations of 4x2 or 6x2, and a maximum laden mass exceeding 16 tons.

The Euro VI standards were established by Regulation (EC) No 595/2009 and further detailed by Regulation (EU) No 582/2011. These standards came into effect at the beginning of 2013 for new approvals and have been updated multiple times to incorporate additional implementation steps.

Compared to the previous Euro V standards, Euro VI introduces stricter emission limits, extended durability requirements, and several new elements, including:

- The World Harmonized Transient Cycle (WHTC) and the World Harmonized Stationary Cycle (WHSC);
- Particle number (PN) emission limits;

- New testing protocols, such as off-cycle and in-use PEMS (Portable Emissions Measurement Systems) testing;
- "In-service conformity" requirements for vehicles and engines;
- More rigorous On-Board Diagnostics (OBD) standards;
- Ammonia (NH_3) concentration limits;
- Measurement of fuel consumption and CO_2 emissions.

Euro VI mandates emission testing using the WHSC and WHTC. It also includes off-cycle laboratory and on-road testing with PEMS. Type-approval testing requirements are as follows:

- WHSC + WHTC tests for diesel engines;
- WHTC tests for positive ignition engines;
- Off-cycle emission (OCE) testing within the WNTE (World Harmonized Not-To-Exceed) control area of the engine map;
- On-road PEMS vehicle tests.

Additionally, the regulation requires in-service conformity (ISC) testing with PEMS on the road, conducted under various driving conditions (urban, rural, and motorway). ISC testing must be done within 18 months of an engine type's first registration in the EU, on vehicles that have accumulated at least 25,000 km. Stage E of Euro VI also includes a cold start requirement, with emissions evaluations starting at lower temperatures [13].

To evaluate compliance, the emissions are averaged using the moving averaging window (MAW) method. Under the MAW method, mass emissions are calculated for subsets of a complete data set, called windows. The window size is defined by the work, or CO_2 emissions, over the window, which must be equal to those of the WHTC. The windows are valid for compliance purposes if the following conditions are met:

A vehicle is deemed compliant if the average emissions of at least 90% of all valid windows are below the ISC limit. The ISC limit is a function of the type-approval limit over the WHTC, multiplied by a conformity factor (CF).

The Euro VI provisions for ISC PEMS testing are phased-in over several implementation steps. The corresponding stages of the emission standards are referred to as Euro VI-A through Euro VI-E. Starting in Euro VI-E, PEMS testing must be carried out using a cold start, with emissions evaluations beginning at a lower temperature of 30°C, and a conformity factor of 1.63 is set for PN.

For what the emission limits is concerned, there is a limit of Ammonia (NH_3) concentration of 10 ppm (parts per million), maximum limit of nitrogen dioxide (NO_2) defined by application regulation, and a limit of the particle number (PN) which is $8x10^{11}$ particles for WHSC test cycle and $6x10^{11}$ for WHTC test cycle.

In the following tables is reported a summary about emission standards with the respective actuation date and test cycle. There are two sets of emission standards:

- steady - state cycle: applied to diesel engines - “standards of steady - state test”;
- transient cycle: applied both to diesel and natural gas engines – “standards of transient test”.

STAGE	DATE	TEST	CO	HC	NOx	PM	PN (Particle number)	SMOKE
			g/kWh				1/kWh	1/m
EURO I	1992, < 85 kW	ECE R49	4.5	1.1	8.0	0.612	-	-
	1992, > 85 kW		4.5	1.1	8.0	0.36	-	-
EURO II	October 1995		4.0	1.1	7.0	0.25	-	-
	October 1997		4.0	1.1	7.0	0.15	-	-
EURO III	October 1999, EEVs only	ESC & ELR	1.5	0.25	2.0	0.02	-	0.15
	October 2000		2.1	0.66	5.0	0.10 (a)	-	0.8
EURO IV	October 2005		1.5	0.46	3.5	0.02	-	0.5
EURO V	October 2008		1.5	0.46	2.0	0.02	-	0.5
EURO VI	31 December 2012	WHSC	1.5	0.13	0.4	0.01	$8x10^{11}$	-

a. for engines of less than 0.75 liters swept volume per cylinder and a rated power speed of more than 3000 rev/min

Note: EEV – enhanced environmentally-friendly vehicles

TABLE 1.2 - EU EMISSION STANDARDS FOR HD DIESEL ENGINES (STEADY-STATE CYCLE)

STAGE	DATE	TEST	CO	NMHC	CH_4 [a]	NOx	PM (b)	PN
			g/kWh				mg/kWh	1/kWh
EURO III	October 1999 EEV only	ETC	3.0	0.40	0.65	2.0	20	-
	October 2000		5.45	0.78	1.6	5.0	160	-
EURO IV	October 2005		4.0	0.55	1.1	3.5	30	-
EURO V	October 2008		4.0	0.55	1.1	2.0	30	-
EURO VI	January 2013	WHTC	4.0	0.16[c]	0.5	0.46	10[d]	$6x10^{11}$

a. For gas engines only (Euro III-V: NG only; Euro VI: NG + LPG).
b. Not applicable for gas-fueled engines at Euro III-IV stages
c. THC for diesel engines only
d. PN limit for gas engines applies for Euro VI step B and later

Table 1.3 - EU emission standard for HD vehicles diesel and gas (transient cycle)

STEP	Implementation dates			ISC PEMS requirements				
	New Types	All vehicles	Last possible registration	PEMS power threshold	Cold start required in PEMS	Min. coolant temperature	CF gaseous pollutants	CF PN
A	Jan. 2013	Jan. 2014	Aug. 2015	20% of max. power	No[a]	70°C	1.50	-
B (CI)	Jan. 2013	Jan. 2014	Dec. 2016					
B (PI)	Sept. 2014	Sept. 2015	Dec. 2016					
C	Jan. 2016	Jan. 2017	Aug. 2019					
D	Sept. 2018	Sept. 2019	Dec. 2021	10% of max. power				
E	Jan. 2021	Jan. 2022	-		Yes[b]	30°C		1.63

a. Evaluation starts when coolant temperature reaches 70°C
b. Evaluation starts when coolant temperature reaches 30°C

Table 1.4 - Euro VI steps and ISC requirements

Effective since October 2005 for new type approvals, and since October 2006 for all engine sales and registrations, manufacturers should demonstrate that engines comply with the emission limit values for useful life periods that depend on the vehicle category, as shown in the following table:

Vehicle category #	Period *	
	Euro IV-V	Euro VI
N1 AND M2	100,000 km / 5 years	160,000 km / 5 years
N2 N3 ≤ 16 ton M3 Class I, Class II, Class A, and Class B > 7.5 ton	200,000 km / 6 years	300,000 km / 6 years
N3 > 16 ton M3 Class III, and Class B > 7.5 ton	500,000 km / 7 years	700,000 km / 7 years
# Mass designation (in metric tons) are the maximum technically permissible mass * km or year period, whichever is sooner		

TABLE 1.5 - EMISSION DURABILITY PERIODS

type approvals also require confirmation of the correct operation of the emission control devices during the normal life of the vehicle under normal conditions of use, also known as "conformity of in-service vehicles properly maintained and used" [13].

1.5 Fuel consumption/CO_2/Greenhouse gas emissions

Lorries, buses, and coaches contribute to over a quarter of greenhouse gas (GHG) emissions. Despite advancements in powertrain technology and improved fuel efficiency in recent years, emissions continue to rise due to increasing road freight traffic.

To address the climate crisis, targeted actions are needed to reduce CO2 emissions in this sector. The European Commission is proposing new targets to align with the EU's climate and zero pollution goals while reducing reliance on fossil fuels.

In 2023, the Commission proposed a revision of the regulation on CO2 emission standards for heavy-duty vehicles. If adopted, this revision would implement stricter CO2 emission standards for heavy-duty vehicles from 2030 onwards and expand the regulation to include smaller trucks (e.g., garbage trucks), city buses, long-distance coaches, and trailers. The image below illustrates the new emission targets. [16].

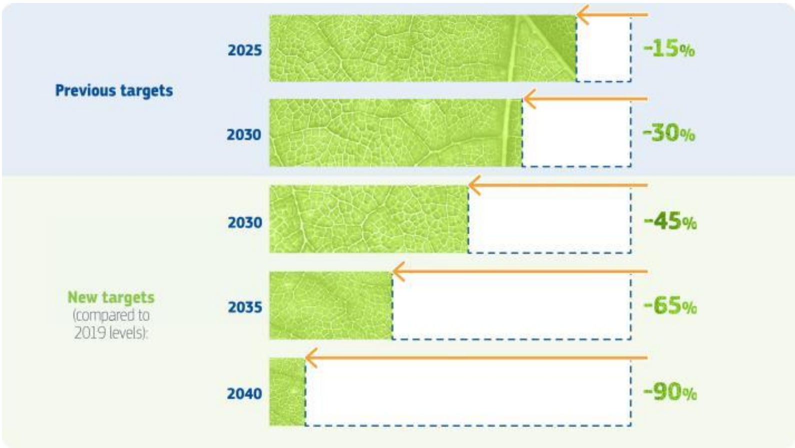

FIGURE 1.7 - NEW CO2 EMISSION TARGETS

To align with the EU's climate goals for 2030 and beyond, the Council and Parliament have upheld the emission reduction targets set by the European Commission. These targets are:

- 45% reduction by 2030;
- 65% reduction by 2035;
- 90% reduction by 2040.

These targets are benchmarked against the 2019 levels. Under the current regulation, the targets were set at a 15% reduction by 2025 and 30% by 2030, applying to heavy trucks over 7.5 tons and coaches. Until the revised regulation is adopted, the existing standards on CO2 emissions for heavy-duty vehicles remain in effect, meaning new engine families must comply with these existing CO2 limits. This regulation has been in force since August 14, 2019.

The 2025 target can be met using current technologies, while the 2030 target was evaluated during the regulation review. Initially, CO2 emission standards cover large lorries, which are responsible for over 73% of CO2 emissions from heavy-duty vehicles. Manufacturers must meet individual targets based on their fleet-wide average CO2 emissions for new lorries registered each year. These specific targets are calculated as a percentage reduction from the EU average during the reference period.

Financial penalties for non-compliance are set at €4,250 per gCO_2/tkm in 2025 and €6,800 per gCO_2/tkm in 2030. To support these targets, the regulation includes incentives for Zero Emission Vehicles (ZEVs) and Low Emission Vehicles (LEVs). ZEVs are defined as lorries without an internal combustion engine or with an engine emitting less than 1 g of CO_2 per kWh per km. LEVs are lorries with a maximum laden mass of over 16 tons and CO_2 emissions less than half of the average emissions of all vehicles in their group registered in the 2019 reporting period.

A super-credits system is in place from 2019 to 2024 to encourage the adoption of ZLEVs, with a multiplier of 2 for ZEVs and 1 to 2 for LEVs based on their CO_2 emissions. This system caps at 3% to maintain environmental integrity. From 2025 onwards, a benchmark-based crediting system replaces the super-credits system, with a 2% benchmark. The benchmark for 2030 will be set during the 2022 review.

Manufacturers' average specific CO_2 emissions are adjusted if the share of ZLEVs in their new heavy-duty vehicle fleet exceeds the 2% benchmark, with at least 0.75 percentage points being vehicles subject to CO_2 targets. Each percentage point above the benchmark reduces the manufacturer's average specific CO_2 emissions by one percent. This mechanism excludes buses and coaches, which have a target of 100% CO_2 reduction by 2030.

The regulation also includes measures to help companies implement these standards cost-effectively, such as:

- banking and borrowing of emissions credits;
- emission balancing among different vehicle groups in the manufacturer's product portfolio;
- exemptions for vocational vehicles (e.g., garbage and construction lorries).

To support the implementation of emission standards, two key measures are:

- certification regulation for determining CO_2 emissions and fuel consumption of new lorries;
- european Regulation 2018/956 on monitoring and reporting.

The monitoring and reporting regulation requires EU Member States to report information on newly registered heavy-duty vehicles. Additionally, manufacturers must report CO2 emission and fuel consumption data for each new vehicle produced for the EU market. The collected data, along with other technical information such as aerodynamic drag, are published by the European Environmental Agency on behalf of the Commission, starting from 2021 [16].

1.5.1 VECTO software

Since the heavy-duty vehicle sector is very diverse, with a significant number of different vehicle types and models and a high degree of customization. The European Commission has conducted an in-depth analysis of the options available to measure the CO2 emissions and fuel consumption of such vehicles.

The conclusion of this analysis was that the easiest option was to use simulation software to obtain unique data for each vehicle produced, the CO2 emissions and fuel consumption of heavy-duty vehicles [37].

The software is called Vehicle Energy Consumption Calculation Tool (known as VECTO). VECTO is a simulation software that has been developed by the European Commission in close cooperation with stakeholders. It is used for the measurement of CO_2 emissions and fuel consumption of heavy-duty vehicles with a gross vehicle weight above 3500 kg. The tool is also capable of setting the mission profile (e.g. long haul, regional delivery, urban delivery, etc.) of vehicles, based on input data from relevant vehicle components [16].

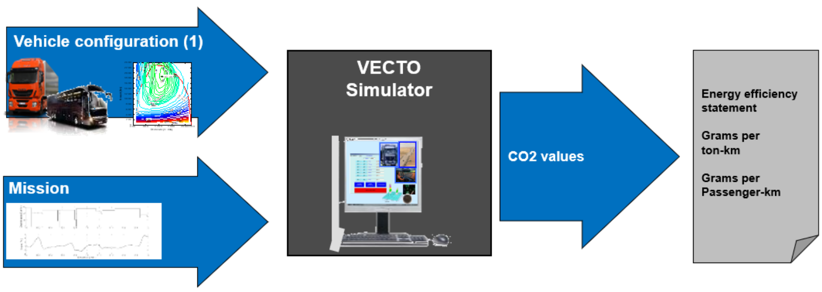

FIGURE 1.8 - CO2 EMISSION MEASUREMENT

VECTO, to compute CO_2 emissions, receives vehicle technical data and mission information as input. After the computations, it gives back the CO_2 values (expressed in grams per ton and per km, but also grams per passenger per km) and fuel consumption of the vehicle for a given mission profile.

Some of the input data about vehicle configuration are the following:

- engine data;
- transmission components;
- axles;
- auxiliary devices;
- tires;
- rolling resistance;
- air drag;
- masses and inertias;
- gearbox friction;
- auxiliary power;
- engine performance.

For what the mission input data is concerned, five different mission profiles for trucks and five for buses have been developed and implemented in the tool, to better reflect the current European fleet. The mission profiles are basically a collection of speed values for each instant of time, represented in a speed versus time chart.

In the following pictures the vehicle segmentation is better clarified. The vehicles considered are trucks, buses, and coaches with gross weight larger or equal to 7.5 tons.

Vehicle cycle	Description	Yearly run distance (km)
Long haul	Delivery to national and international sites (mainly highway operation and a small share of regional roads).	135.000
Regional delivery	Regional delivery of consumer goods from a central warehouse to local stores (innercity, suburban, regional and also mountain roads)	60.000
Urban delivery	Urban delivery of consumer goods from a central store to selling points (innercity and partly suburban roads)	40.000
Municipal utility	Urban truck operation like refuse collection (many stops, partly low vehicle speed operation, driving to and back to central base point)	25.000
Construction	Construction site vehicles with delivery from central store to very few local customers (innercity, regional roads; minor share off-road driving)	60.000

FIGURE 1.9 - TRUCKS SEGMENTATION (MASS > 7.5 TON)

Vehicle segment / cycle	Description	Average yearly run distance (km)	kg/passenger
City Class I – heavy urban, urban, suburban		60.000	68
Interurban Class II		60.000	71
Coach Class III		80.000	71

FIGURE 1.10 - BUSES AND COACHES SEGMENTATION

2. Project specifications and technology

In this chapter it will be presented the case study of this thesis work, which is a new heavy duty engine family for on-road applications, realized by FPT Industrial.

A brief description of the company in which this work has been conducted is proposed. After that, a description of the main characteristics of the engine, as well as the new content that ensures the sustainability goals imposed by the most recent environmental provisions, will be reported.

The calibration parameters of the engine and related working strategies, that allow the engine to comply with the current Euro VI Step E emission regulation, will be clarified. Together with the engine architecture, an overview of the after-treatment system construction will close the chapter.

2.1 Iveco Group

The work done for this study has been conducted in cooperation with IVECO GROUP, specifically in FPT Industrial. Iveco Group is one of the world's largest capital goods companies that operates in the field of commercial and special vehicles, propulsion systems and related financial services.

Iveco Group is composed of several brands, such as IVECO, FPT Industrial, Heuliez, Iveco Bus, Iveco capital, Iveco Defense Vehicles (IDV), Astra and Magirus. It presents 20 industrial sites and 29 Research & Development centers all over the world.

The plants of Iveco Group implement World Class Manufacturing, adopting a continuous improvement philosophy, developed through the reduction of waste, and the attention paid in the increase of the quality of the products.

FPT Industrial is the brand devoted to the production of engines, transmissions, axles, and E-Powertrain for industrial, agricultural, marine, and commercial vehicles.

FIGURE 2.1 - IVECO GROUP LOGO AND ITS BRANDS

2.2 Heavy duty diesel engine for on road applications

The case of study of this work is the new heavy duty engine family for on-road vehicles. It was presented to the public during the International Automobile Exhibition of Hannover, Germany, in 2022. This engine family was meant to revolutionize FPT Industrial's propulsion offering, responding to the new needs of the engine segment, induced by the most recent sustainability constraints imposed by the European Union.

FIGURE 2.2 – ENGINE REAR VIEW

Investments in the development of new engines have to meet a twofold need. On the one hand, to ensure the development of products capable of amortizing the resources allocated to their development in the long term, ensuring the required standards. On the other hand, to ensure the competitiveness of the new generation of internal combustion engines in a context of extremely dynamic technological landscape, which for the moment doesn't see a definitive solution.

The new engine family is based on an innovative engine platform, that was born with a multi-fuel and multi-purpose perspective. The engine will be adapted for industrial vehicles in the on-highway, off-road, and marine segments. The platform modularity allows the engine to be capable of adapting to the most several applications, intervening only on 20% of all its components. It is designed to run on diesel, natural gas, biofuels and in the future, hydrogen. This new engine platform is considered a strategic product, since it represents a primary contributor to achieving CO_2 emission targets and is one of most relevant parts of the group's decarbonization program [18].

The targets set by the platform department for the new engine family, in random order, can be summarized as follows:

- reduction of CO_2 emissions;
- weight reduction;
- high braking power (obtained through the engine valvetrain, this allows, in some cases, to eliminate the auxiliary braking systems, like intarder/retarder);
- serviceability (intended as extension of the maintenance intervals).

2.2.1 New contents

This new engine platform is a project that leads to the birth of a new generation of internal combustion engines. In terms of design, the engine is completely renewed with respect to the current products, as the only points in common are the in-line six-cylinder architecture and the displacement.

The insight of the following pages deals with the engines that run with conventional fuels, focusing the attention on the diesel version.

In the next picture, the highlight of all the new contents are shown.

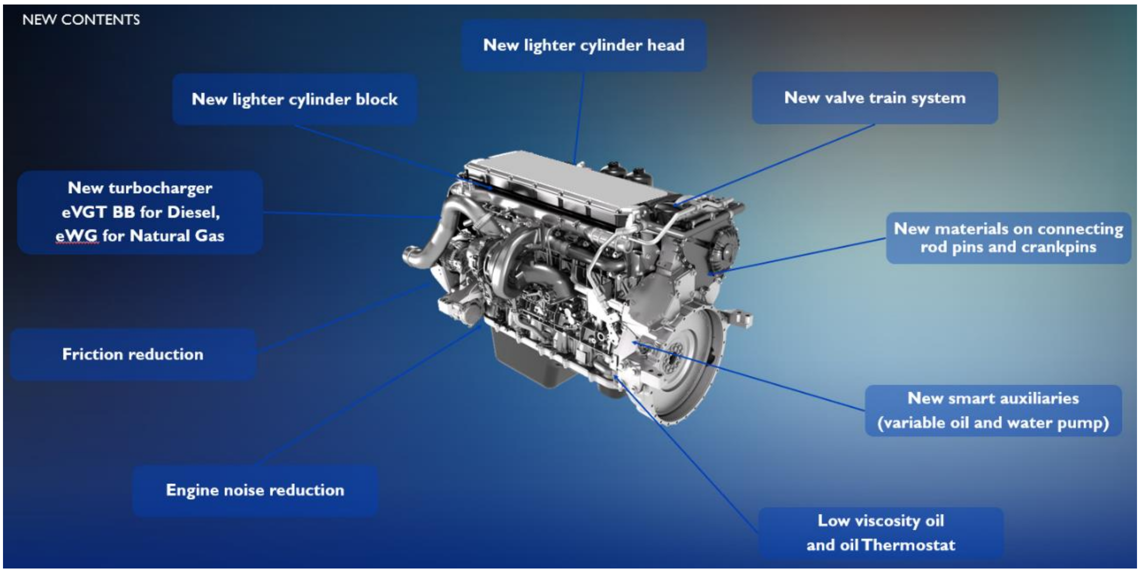

FIGURE 2.3 - NEW CONTENTS

New lighter cylinder head and cylinder block

The cylinder head and cylinder block are made of a new material, from standard Grey Cast Iron to Compacted Graphite Iron casting (CGI). The new cast iron, also known as “vermicular cast iron”, is a material that falls between the conventional lamellar cast iron and the more valuable ductile iron. CGI is characterized by shorter, thicker, and rounded edges of graphite particles. This permits stronger adhesion of compacted graphite clusters into the iron matrix. The crack initiation, as well as the propagation, is dramatically reduced.

FIGURE 2.4 - CYLINDER HEAD

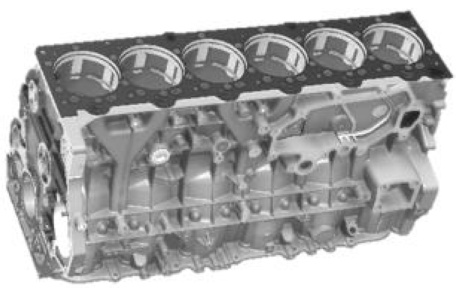

FIGURE 1.5 - CYLINDER BLOCK

At the end, the material ensures better physical and performance characteristics, and therefore offers higher mechanical resistance properties than the traditional ones. This allowed to reduce the wall thickness of components by lowering masses by about 10% compared to the previous generation [18].

Engine	Weight [kg]
New	88,8%
Old	100%

FIGURE 2.6 – ENGINE WEIGHT COMPARISON

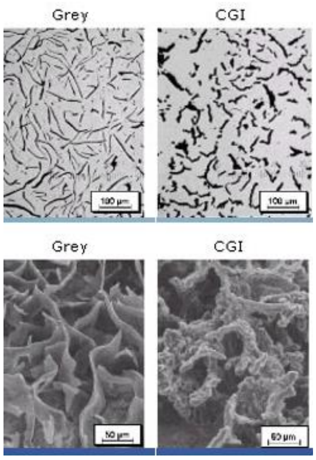

FIGURE 2.7 - GREY CAST IRON VS CGI

New turbocharger

The engine has been equipped with a new turbocharger for high performance and low fuel consumption. The natural gas version has an electronic wastegate turbocharger (eWG). The diesel engine, on the contrary, has an electronic variable geometry turbine running on ball bearings (eVGT BB). The last solution is very refined since it is based on dual flow turbine volute. There is a partition septum inserted in the component that avoid pressure interference between the gas flows coming from cylinders 1, 2, 3 and 4, 5, 6. The variable geometry allows to optimize the torque delivery over the entire engine speed range, guaranteeing excellent standstill starts, fast transient response, and good elasticity [18].

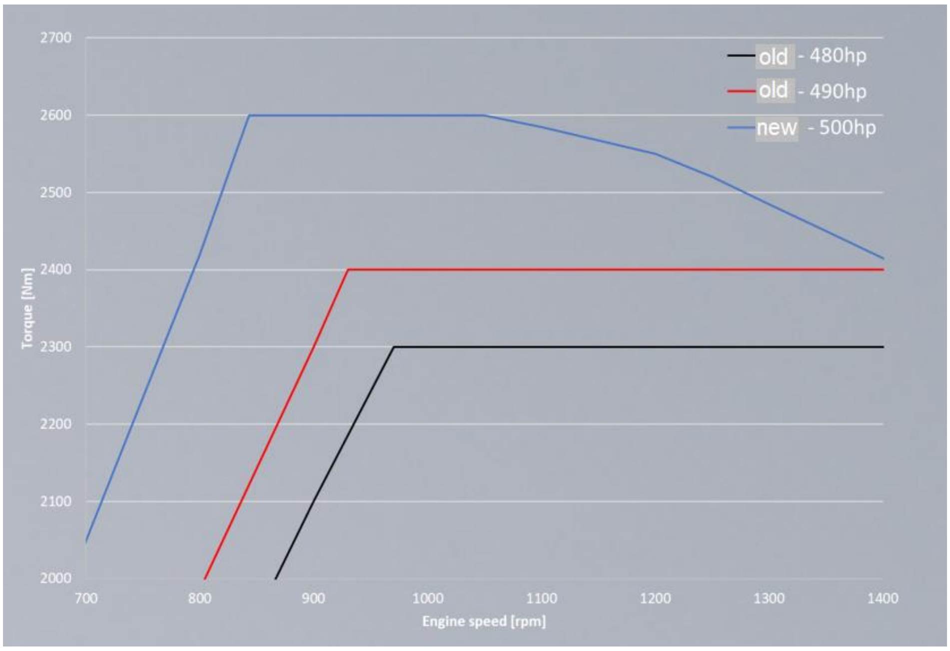

FIGURE 2.8 - TOP SPEC NEW ENGINE TORQUE AND POWER MAP

Looking at the chart it is clear that the new engine reaches higher torque at lower rpms compared to the old ones.

New valvetrain system

The engine has been designed with a new valve train system called High Performance Engine Brake, to achieve high braking power. The new system is available for both the diesel and the natural gas version. The heart of the technology is a new distribution system that uses collapsible rockers. By means of hydraulic control, it modifies the exhaust valves dynamics to take advantage of the compression of the air in the cylinders, when the engine is dragged by the transmission. The objective is to generate braking power without involving mechanical brakes. The engine brake is available in two versions:

- High Performance Engine Brake (HPEB): max braking power of 530 kW and max braking torque of 2470 Nm;
- Medium Performance Engine Brake (MPEB): max braking power of 450 kW and max braking torque of 1930 Nm.

FIGURE 2.9 – VALVETRAIN

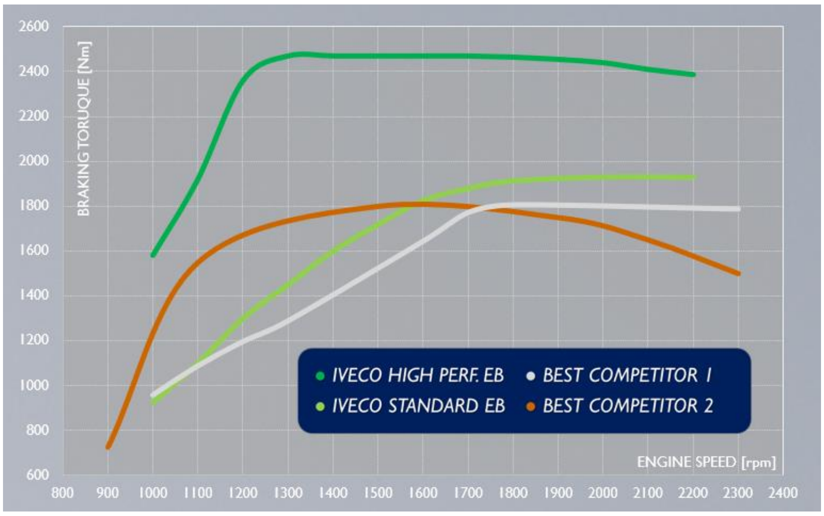

FIGURE 2.10 - ENGINE BRAKE POWER CURVE

The new valve train system ensures an high braking capability, that represents the best in class. This functionality prevents the installation on some categories of commercial vehicles the auxiliary braking systems, i.e. the intarder. The intarder is a heavy, expensive, and relatively complicated system. The possibility to avoid its presence in the trucks allows to save weight, money, and to increase reliability. It is not possible to delete the system from all the commercial vehicles because for some categories it is mandatory, i.e. the vehicles for passenger transportation [18].

Smart auxiliaries

From the point of view of the optimization of the wasted work through auxiliaries, the new engine has been equipped with smart oil and water pumps. They are electrically controlled devices that work with variable flow-mass rates. In a few words, they are able to optimize their power request according to the load of the engine. In this way, if for instance, a truck is doing a cruising mission, the engine run at relatively low speed (around 1000 rpm) and has a moderate load, the pumps work delivering only the necessary water and oil flow rate. The benefits are a reduction in fuel consumption.

Low CO_2 key component contributors

As already stated, the new engine family represents a key contributor to CO_2 emission reductions, to get closer to the 2025 emission targets. The Diesel version brings a CO_2 reduction of 7% with respect to the predecessor, while the methane version 8%. With a focus on the diesel fueled one, to achieve these results, the engineers have set the following technical targets:

- increased P_{rail} up to 2500 bar;
- increased Peak Cylinder Pressure (PCP) up to 250 bar;
- friction abatement;
- smart oil pump;
- smart water pump;
- reduced weight.

Some of the previous targets have already been discussed. For what the fuel pressure is concerned, the pressure in the common rail of the diesel version reaches high values, up to 2500 bar. The fuel injection is managed by a system that ensures high performance and reduced fuel consumption, through a fine fuel atomization performed by the nozzles.

The compression ratio is high, and this allows to reach, in the chamber, combustion pressures in the range of 250÷270 bar. The result is increased efficiency, less consumption for the same power rate, and consequently less CO_2 emissions.

An important work of refinement has been made for what the friction losses is concerned. For every internal combustion engine, friction is very detrimental because it directly affects the torque generation and the fuel consumption.

The friction work is caused by the following phenomena [19]:

- to overcome the resistance to relative motion of all the moving parts of the engine;
- to drive the engine accessories;
- to draw the fresh mixture through the intake system and into the cylinder and to expel the burned gases from the chamber and out of the exhaust system.

In the new engine all the rotating parts, bearings, journal bearings, small plug of connecting rods and plunger rings are new, and they are designed to reduce friction.

The engine oil has new specifics, and it is way less viscous. In this way it facilitates the movements of all the rotating and sliding parts. As already anticipated, from the friction point of view, a great help comes from the smart oil and water pumps.

Last but not least, the adoption of several components made of plastic, such as the airbox, or the pipes of the air induction, together with the use of new CGI casting, contributes to weight reduction. This means saving mass that otherwise has to be dragged, which causes more energy expenditure, especially during vehicle speed transients and standstill starts.

2.2.2 Technical specification

All the diesel versions are equipped with direct injection at the highest pressure and with a turbocharger electrically controlled, with variable geometry system, running on ball bearings (eVGT BB). This ensures the best performances at all engine speeds and fast transient response.

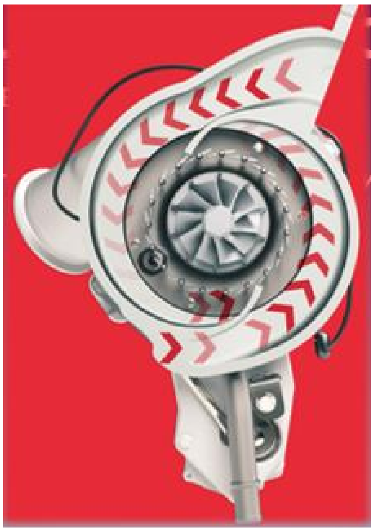

FIGURE 2.11 - EVGT BB TURBOCHARGER CROSS-SECTION

The whole engine family is compliant to the Euro VI emission standard step E, where the step represents “phase in” of the new regulation. The engine that will be homologated and described hereafter is a 12,9 liters diesel engine, delivering 425 kW (577 HP) @1650 rpm.

FIGURE 2.12 – THREE QUARTER VIEW OF THE ENGINE

The engine features an inline 6-cylinder fractionation, with a bore of 135 mm and a stroke of 150 mm. The displacement is 12876 cm^3 (~ 12,9 liters). The injection is performed by an high-pressure Common-Rail system, using new technologies for doing multiple injections. The engine has Multi Point Injection (MPI), so one injector per cylinder, and the fuel pressure accumulation is guaranteed by a Common Rail system (ECR), that in the new engine allows to reach up to 2500 bar.

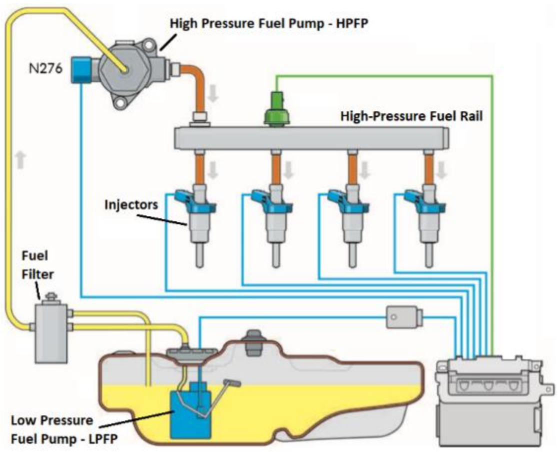

FIGURE 2.13 - COMMON RAIL SYSTEM SCHEME OF AN INLINE 4 ENGINE

The general features of the engine considered are the following:

SPECIFICATIONS	
Application	On-road trucks
Cylinder arrangement	6 Cylinder in line
Valves per cylinder	4
Thermodynamic cycle	Diesel 4 stroke
Injection System	ECR 2500 bar (Electronic Common Rail)
Turbocharger	EVGT BB (Electronic Variable Geometry Turbo Ball Bearing)
Displacement l	12,9
Cooling System	Liquid
Bore x Stroke mm	135 x 150
Peak power kW (HP)@rpm	425 (577) @1650
Peak torque Nm @rpm	2600 @940
ATS	DOC + DPF + SCR + CUC
Certification	Euro VI E

TABLE 2.1 – ENGINE FEATURES

WEIGHT AND DIMENSIONS	
Dimensions mm	1365 x 1069 x 1185 (LxWxH)

TABLE 2.2 – ENGINE DIMENSIONS

The acronyms used for the exhaust system (After Treatment System – ATS) are:

- DOC (Diesel Oxidation Catalyst);
- DPF (Diesel Particulate Filter);
- SCR (Selective Catalytic Reduction);
- CUC (Clean Up Catalyst).

Engine brake

The engine brake represents a feature of fundamental importance in this new engine project. The working principle is the same of the so called "Jack Brake", name that comes from the company that invented this braking system. Considering a four-stroke engine, the system works in the following way. The intake and compression phase happen like normal but, when the piston approaches the top death center (TDC), right after the compression stroke, the exhaust valves open. This is also called "compression release" event. So, instead of letting the combustion of the mixture push down the piston, producing torque down to all the driveline, the exhaust valves opening let the pressure going outside the combustion chamber. In this way, the energy of the combustion is wasted because it is not going to produce useful work. This working principle let the crankshaft slow down, thus decelerating the vehicle [20].

The engine brake fitted in the new engine family represents an evolution of the conventional engine brake. With respect to the previous versions, it can offer 2 compression release events per revolution of the camshaft (instead of 1), and this ensures an enhanced braking capability of 75%.

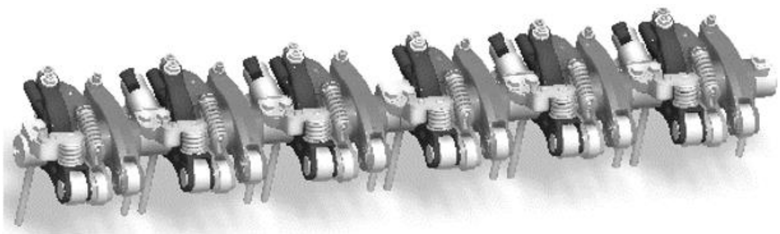

FIGURE 2.14 - ENGINE VALVETRAIN

Engine brake map is shown in the following diagrams, for both HPEB and MPEB.

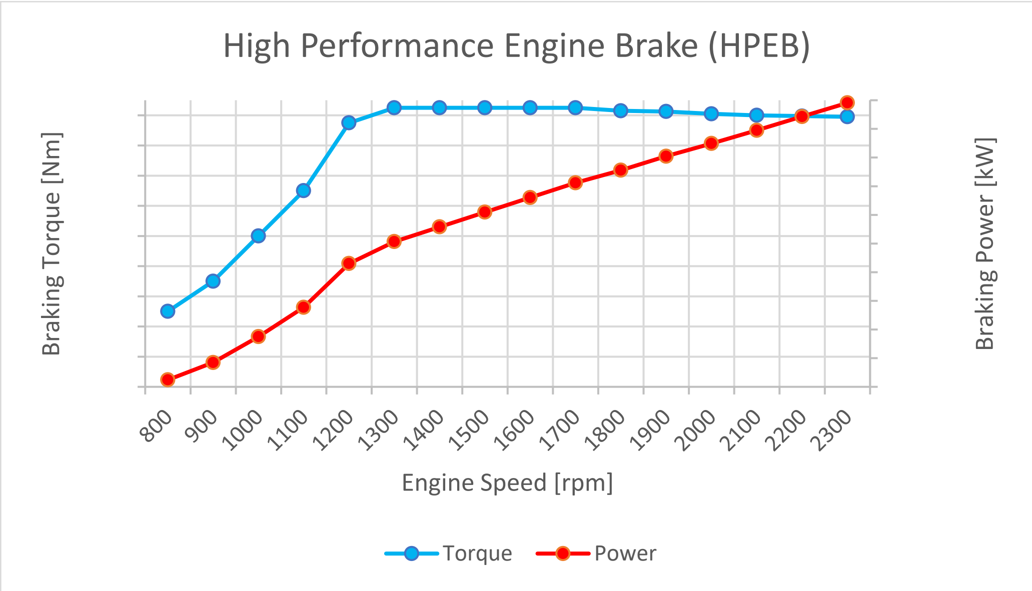

FIGURE 2.15 - HIGH PERFORMANCE ENGINE BRAKE MAP

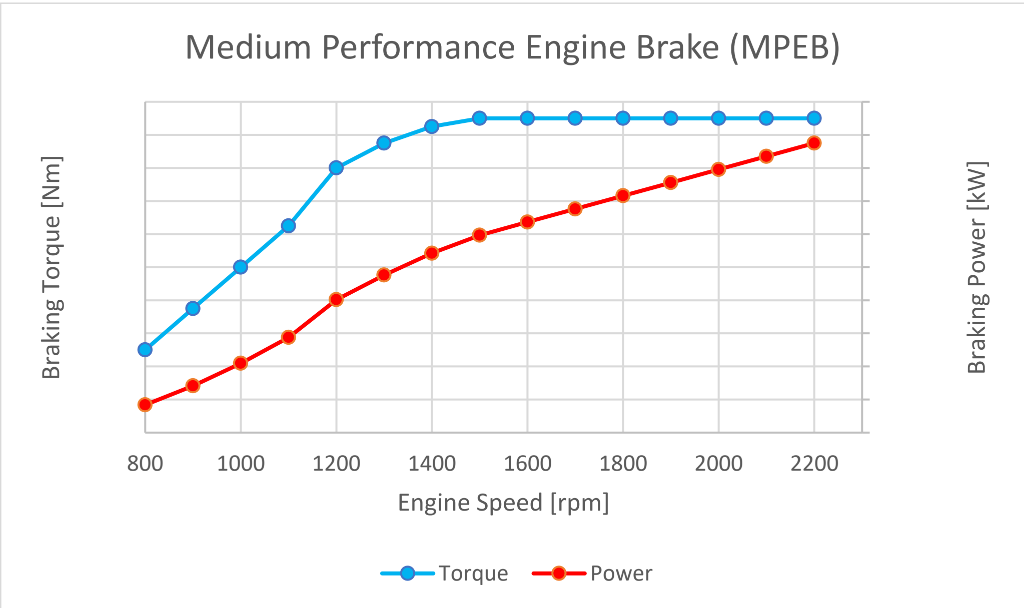

FIGURE 2.16 - MEDIUM PERFORMANCE ENGINE BRAKE MAP

2.2.3 Engine calibration parameters

As said, the engine that will be homologated is compliant with the Euro VI Step E emission standard. For the emission limit compliancy, the engine and the ATS projects are correlated. As a matter of fact, ATS is designed taking into account the calibration parameters of the engine and the exhaust temperature. Generally, the calibration parameters that impact the emissions are mainly related to the fuel injection.

For the specific case of study, the injection is performed by an high-pressure Common-Rail system. It represents a new technology in which a certain degree of innovation has been added to what multiple injections is concerned.

Additional contents connected to the emissions:

- Charge Cooling Valve (CCV). CCV stands for crankcase ventilation, and it's an essential component of the diesel engine. It evacuates the blow-by gases that escape from cylinders and crankcase. These gases are re-routed into the exhaust system, upstream the ATS, and then burned off. This device is mandatory for Euro VI legislation [21].
- Exhaust Flap. In the past, the exhaust flap was used to obtain braking torque through the so-called exhaust brake. The exhaust flap is basically an electrically actuated butterfly valve that nowadays is used for the SCR (ATS) thermal management for cold cycles.

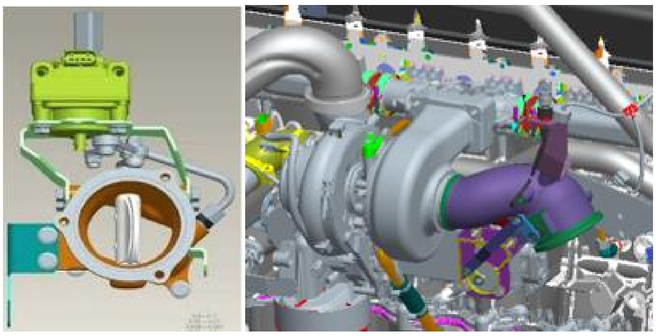

FIGURE 2.17 - EXHAUST FLAP

ICEs represent a major source of environmental pollution. Although the ideal combustion reaction with air of an HC fuel with a generic composition C_aH_b (such as gasoline and diesel fuel) should lead to nontoxic combustion products such as CO_2, water vapor H_2O, nitrogen N_2 and Oxygen O_2 in case of lean mixtures, as shown in the equation 1, the real combustion process in ICEs typically produces pollutant emissions mainly represented by CO, unburned HCs, and nitrogen oxides (NO_x). Moreover, for some combustion processes, solid particles (referred as PM) can be emitted.

The following equation represents an ideal combustion process:

$$C_aH_b + \left(a + \frac{b}{4}\right)(O_2 + 3.773\ N_2) = aCO_2 + \frac{b}{2}H_2O + 3.773\ \left(a + \frac{b}{4}\right)N_2 \quad (1)$$

These pollutant emissions are generated from an amount of non-ideal processes during the combustion process.

These non-idealities are:

- lack of oxygen that leads to the formation of CO;
- oxidation of nitrogen under high temperature conditions that promotes the formation of nitrogen oxides (NO_x);
- incomplete combustion of the fuel trapped into crevices and quench layer, that leads to the formation of unburned HC.

CO_2, although it is a nontoxic combustion product, is considered a greenhouse gas (GHG) and one of the major causes of global warming. For this reason, it is treated as a pollutant and regulated as well. CO_2 emissions are the results of an ideal combustion process for HC fuels and can be controlled only by controlling the amount of fuel burned, or by increasing the engine efficiency [22].

In this paragraph the focus goes to the two main ICE pollutants, which are NO_x and PM. Due to the opposite reaction to combustion temperature, the reduction of one of the combustion products (NO_x or PM) necessarily implies the increase of the other one. In diesel engines it is common to refer to the NO_x/PM trade-off or the NO_x/fuel consumption trade-off.

In cylinder NO_x and PM formation can be controlled through different kind of actions that can be grouped in two families [23]:

- Calibration actions: choice of intake charge (EGR, boost and swirl levels) and fuel injection (injection advance, injection pressure, multiple injections) characteristics at calibration stage;
- Design actions: choice of Common Rail, combustion chamber and nozzle geometries etc. at design stage.

Here the attention will be dedicated to the calibration parameters. To reduce NO_x as requested by the emission regulation Euro VI step E, it is necessary to work on several combustion management parameters and exhaust gas treatment systems (ATS).

There are basically two ways to let a new heavy-duty diesel engine be compliant with the Euro VI regulation: using EGR (Exhaust Gas Recirculation) or the use of an after-treatment system called SCR (Selective Catalytic Reducer).

Exhaust gas recirculation (EGR) is an emission control technology, by which a portion of engine's exhaust gas is returned to the combustion chamber via the intake system to reduce NO_x emissions, thanks to a considerable peak temperature decrease of the diesel combustion flame. The temperature decrease worsens the combustion efficiency, thus leading in penalties in the fuel consumptions. Increasing the EGR rate, however, leads also to an adverse influence on particulate matter emissions [23]. As shown in the picture below, after a certain threshold value of EGR percentage, the PM mass rate increases dramatically.

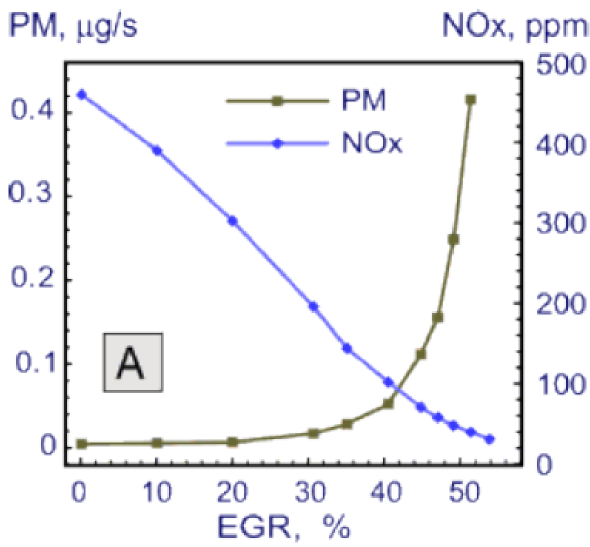

FIGURE 2.18 - PM AND NOX VS EGR RATE *

Together with the mass rate, even the particulate number increases. Increasing EGR results also in production of larger particle size. Indeed, the reintroduction of EGR particles in the combustion chamber act as nuclei for new ones, and they agglomerate to form larger particles.

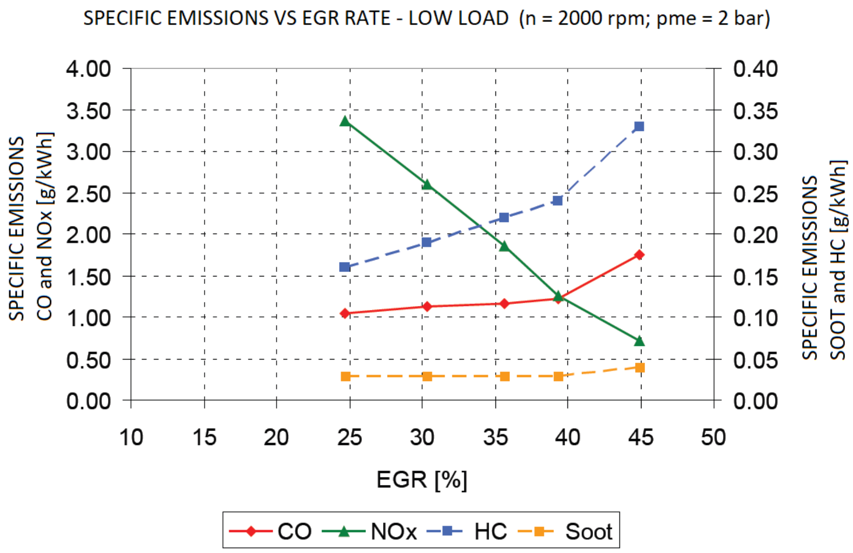

FIGURE 2.19 – SPECIFIC EMISSIONS VS EGR AT LOW LOAD *

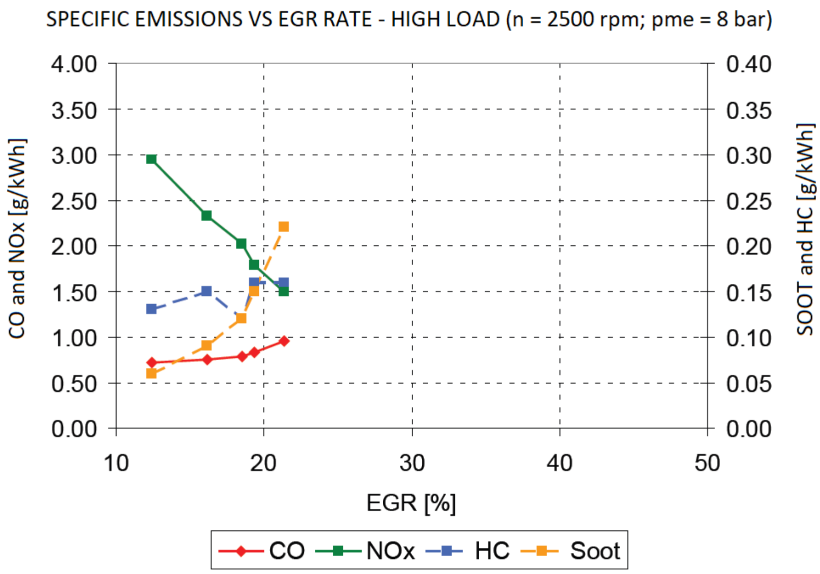

FIGURE 2.20 - SPECIFIC EMISSIONS VS EGR AT HIGH LOAD *

As it is noticeable from the graphics, penalties to be paid in terms of CO, HC and soot depend on engine operating point: at lower loads, diesel engines tolerate higher EGR ratio because the exhaust is still rich of oxygen while at higher loads the oxygen is scarce and inert constituents becomes predominant.

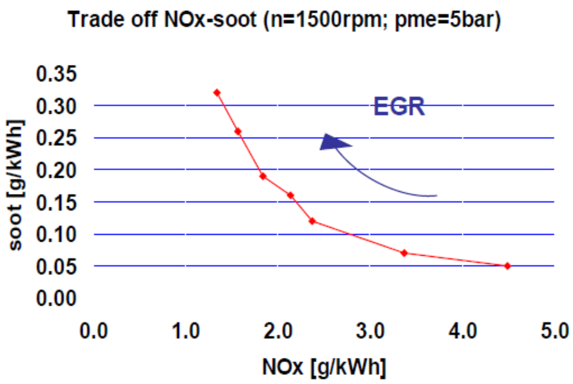

FIGURE 2.21 – SOOT VS NOX *

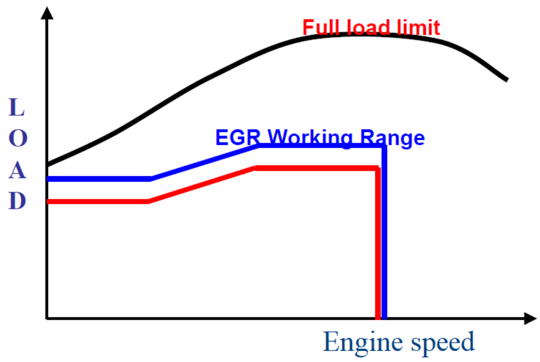

FIGURE 2.22 – EGR WORKING RANGE *

According to the diagram above, EGR is suitable for engines that work at medium load. Since homologation cycles of heavy-duty engines include full-load engine phases, the use of EGR is not suggested.

Exhaust gas recirculation, in general, causes a reduction of oxygen in the combustion chamber. Consequently, the combustion efficiency is lower, and the PM formation is higher.

Another important parameter is the start of injection (SOI), that is the moment when the fuel is injected in the combustion chamber. The injection timing affects the PM and NOx formation. In the picture below it is possible to see the NOx/PM trade-off curve, as function of the injection timing advance (expressed in crank angle degrees):

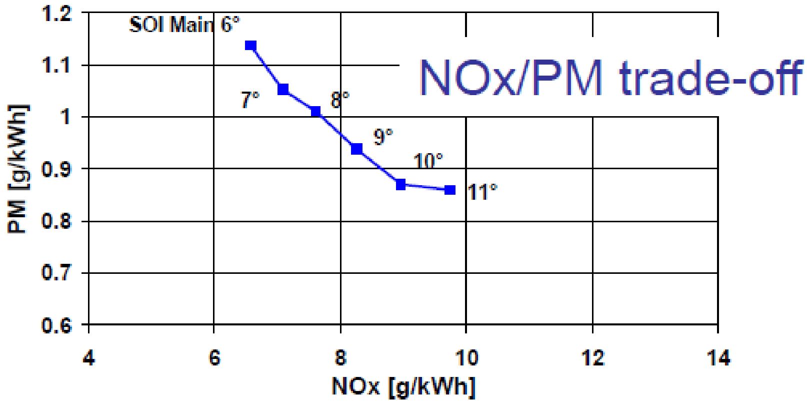

FIGURE 2.23 - PM/NOx TRADE-OFF AS FUNCTION OF SOI *

If the injection timing is increased (the earlier the fuel is injected), the ignition delay becomes longer, and the premixed portion of the fuel prior to ignition becomes greater. This means that the fuel accumulation increases and has more time to mix with air. When the condition for the auto ignition is reached, the peak temperature of the pre-mixed combustion sees an abrupt increase. The result is that PM has more time to be oxidized and the specific emissions decrease.

The next parameter to be accounted is the injection pressure (IP). An increase in the injection pressure causes a better atomization of the fuel spray. The injection rate increases as well, reducing the time to introduce the same fuel quantity in the combustion chamber. Therefore, there is an increase in the fast-burning premixed combustion phase. This effect, combined with a proper selection of the injection timing advance, leads to improvements in fuel consumption and particulate emissions, as shown in the following graphs [23].

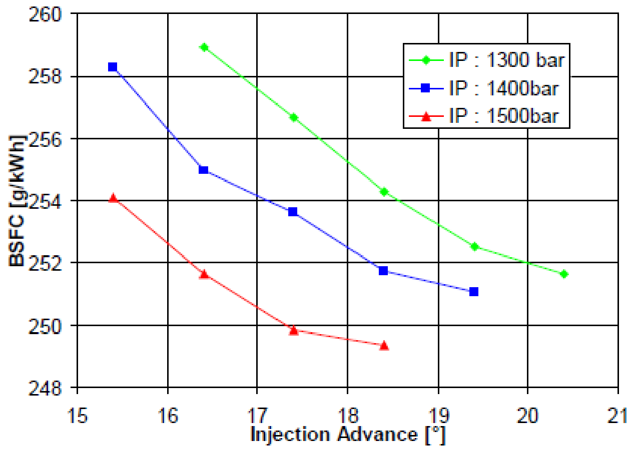

FIGURE 2.24 - BSFC VS SOI AS FUNCTION OF IP *

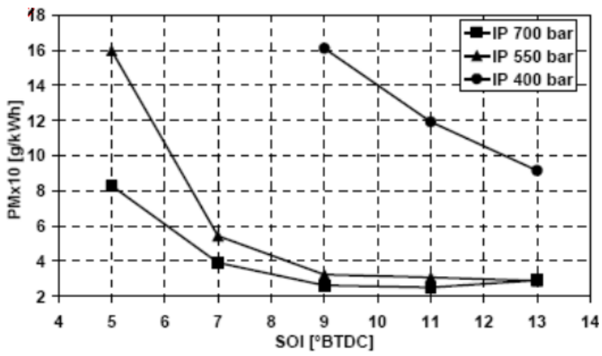

FIGURE 2.25 - PM10 VS SOI AS FUNCTION OF IP *

Looking at the last diagram, if the injection timing advance is increased, the injection pressure doesn't have much influence on the PM formation. So, advancing the fuel injection, it is also possible to work on moderate values of IP.

In addition to this, the injection pressure increase negatively affects NO_x emissions. Indeed, they rise rapidly, due to the increased peak pressure and temperature in the combustion chamber. For this reason, a suitable PM vs NO_x trade-off must be reached, through a proper calibration of the control parameters [23]. According to a study of the Society of Automotive Engineers (SAE), the best compromise to keep specific emissions low is to act on the injection timing, setting SOI between 7 and 9 crank angle degrees, with an injection pressure value of 550 bar.

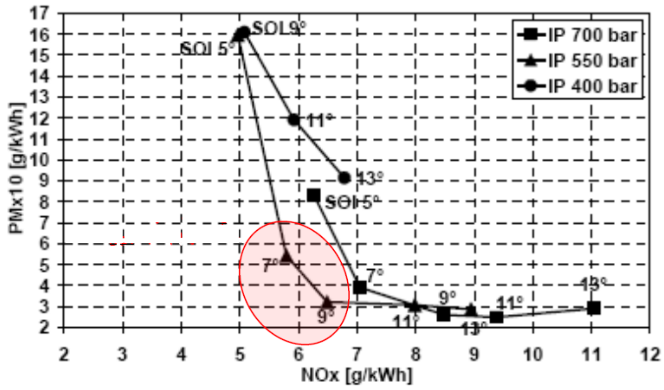

FIGURE 2.26 - PM VS NOX AS FUNCTION OF INJECTION TIMING FOR DIFFERENT IP CURVES *

The injection pressure increase leads to a decrease in the inlet turbine temperature. If this is detrimental for performance and turbocharger efficiency, it may be positive for the durability of turbine itself. Indeed, a low inlet temperature value reduces the wear of turbine blades.

The main problem of the injection pressure increment seems to be the combustion noise. To solve this problem, there are several strategies. One of these is the injection rate shaping, a technique that is used to control the rate at which fuel is injected in the combustion chamber during the injection process. By carefully shaping the injection profile, it is possible to influence various aspects of combustion, including combustion noise. The shaping can be performed in several ways. Among these there is the control of fuel delivery and the adding others injection events to the main injection. About the latter, the injection shaping can involve pre-injection and post-injection events to the main one. Pre-injection, also called pilot, introduces a small amount of fuel into the combustion chamber before the main injection. If properly timed, the pilot promotes a more gradual combustion process and reduces noise. This happens because it increases pressure and temperature in the chamber. A second pilot can be added to dispose the fuel accumulation due to the previous injection.

The post-injections are used in internal combustion engines for various purposes. They can help to reduce the smokiness. Injecting fuel after the main injection, it is possible to have a more complete combustion of the residual mixture, reducing PM emissions. Post-injections are also used to control exhaust temperature. By adding a post-injection to the main, it is possible to increase the exhaust gases temperature to improve the after-treatment systems efficiency [23].

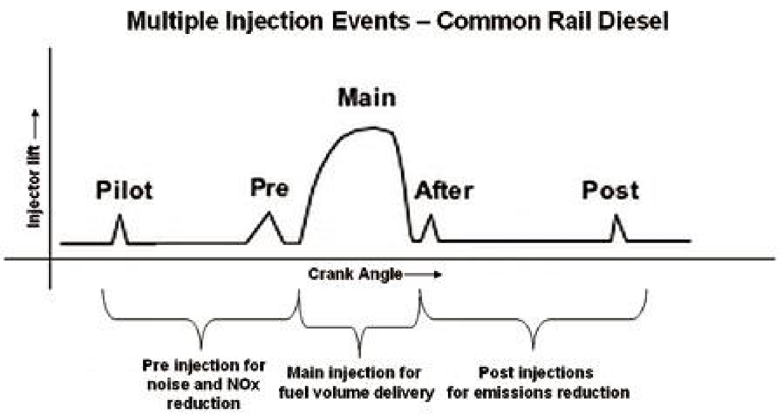

FIGURE 2.27 - MULTIPLE INJECTION EVENTS *

In the FPT industrial mindset, the focus has always been on the engine performances and fuel consumption. The thirty-year-old design philosophy is based on the avoidance of the use of EGR systems, and it is more focused on reaching an efficient combustion.

Since FPT industrial have always had strong technology on ATS side, the design of the internal combustion engine leads to have a combustion shifting to low CO_2 and soot production. An efficient selective catalytic reducer, using urea, will take care of the higher NO_x production, and even low PM emissions will be drastically lowered by the presence of a particulate filter.

* The pictures are taken from the PowerPoint slides of the course of Engine Emission Control of Professor Federico Millo, Politecnico di Torino.

2.2.4 After treatment system HI-eSCR

The after-treatment system (ATS) of the new engine family (on-road) is a device that allows the vehicle to be compliant with the Euro VI step E regulation. ATS is a system composed of several elements that have the aim to reduce the pollutant emissions of the internal combustion engine. The system mounted in the new engine is the patented system called HI-eSCR. This is an assembly aimed at guaranteeing low emissions, low fuel consumption and best in class performance. In the following picture it is possible to see the scheme of the main components contained in the HI-eSCR.

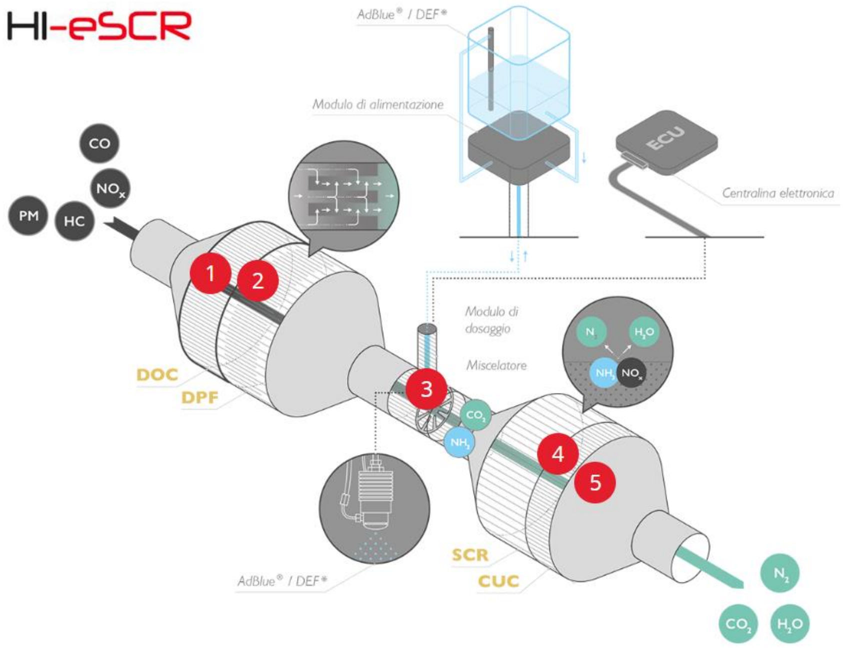

FIGURE 2.28 - HI-ESCR SCHEME

According to the numbers depicted in the image, the main components of the HI-eSCR are:

1. Diesel Oxidation Catalyst (DOC);
2. Diesel Particulate Filter (DPF);
3. ADBLUE® / DEF injection (Ad-blue dosing module and mixer);
4. Selective Catalytic Reduction (SCR);
5. Clean-up Catalyst (CUC).

The HI-eSCR system appears as a big box, also known as SCRT, in which all the components of the after-treatment system are grouped. In the following pictures the three-quarter and top views of the system are shown.

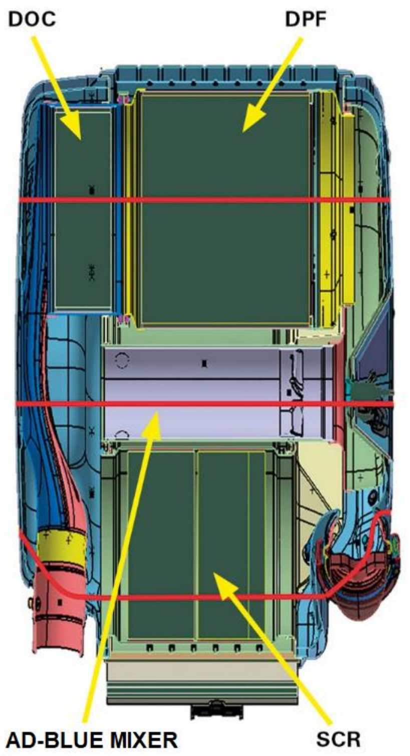

FIGURE 2.29 - SCRT TOP VIEW

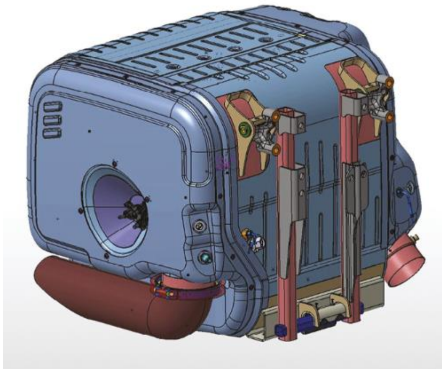

FIGURE 2.30 - SCRT THREE-QUARTER VIEW

A description of the main components will follow.

1) Diesel oxidation catalyst

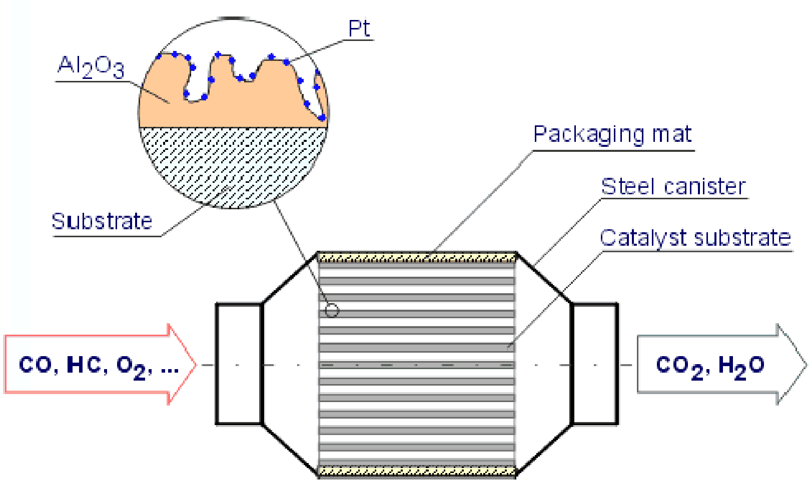

FIGURE 2.31 - DIESEL OXIDATION CATALYST *

Diesel oxidation catalyst (DOC) is a device that, with sufficient high exhaust temperature, allows to oxidize unburned hydrocarbons (HC) and carbon monoxide (CO) with an efficiency of about 90%. The DOC activity extends to compounds like polynuclear aromatic hydrocarbons (PAH) and or the soluble organic fraction of diesel particulate (SOF). Another reaction that takes place in the DOC is the NO oxidation into NO_2. This element will play an important role in the next exhaust gas treatments. Diesel oxidation catalyst may be effective also in controlling the diesel odor [24].

The reactions that take place in the catalyst are the following:

$$CO + \frac{1}{2}O_2 \rightarrow CO_2$$

$$HC + O_2 \rightarrow CO_2 + H_2O$$

$$PAH + O_2 \rightarrow CO_2 + H_2O$$

$$Aldehydes + O_2 \rightarrow CO_2 + H_2O$$

$$2NO + O_2 \rightarrow 2NO_2$$

2) Diesel particulate filter

The diesel particulate filter is an exhaust gas purification system that traps particulate produced by diesel engines and prevent its release in the atmosphere. It allows to reduce the soot and the black smoke emissions.

The device installed in the HI-eSCR exhaust system is of the wall through type, and it operates like a mechanical filter, blocking solid particles in the gas stream. The novelty of this model year 2024 is the new substrate material and coating, in order to enhance the particulate number filtration capacity.

The filter is made with channels that are alternatively plugged at the ends to force the gas through the porous walls, where the particulates are mechanically trapped. This structure is known as "wall-flow", and it is shown in the following picture.

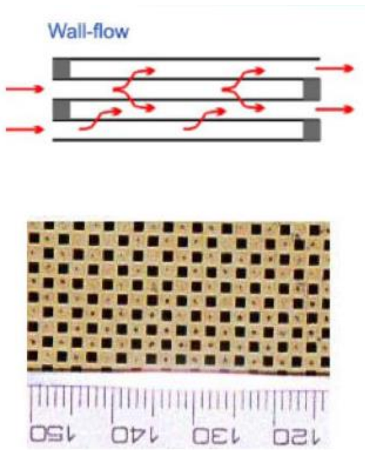

FIGURE 2.32 - WALL-FLOW SUBSTRATE *

The filtration mechanism occurs in two steps. First, the exhaust gases are filtered passing through the porous wall, by means of the so-called depth filtration. Afterwards, once the first layer of the porous media has been saturated, soot accumulates on the wall. The soot layer, which continuously grows up, contributes to the particulate filtration through the "cake filtration" [24].

The two mechanisms cause different pressure drop increases, more rapid at the beginning and then almost linear in the time. Therefore, the accumulation of particles may cause filter clogging that affects the engine operation.

For this reason, the diesel particulate filter must undergo a periodic removal of the accumulated particulate, to restore its soot collection capacity. This removal is called regeneration, and it can occur either continuously or periodically.

The filter regeneration consists in the burning of the soot accumulated in the trap. The problem is that temperatures above 600 °C are necessary to burn the soot, and the exhaust gas stream of a diesel engine struggles to reach such temperature levels, especially when the engine is expected to work at partial load. This aspect requires the adoption of specific regeneration techniques to increase exhaust temperatures [24].

The HI-SCR system comprises a catalyzed DPF that works with low backpressure and reaches high regeneration efficiency. The strategy implemented by FPT to let the engine be compliant to the Euro VI step E regulation involves the continuous regeneration of the filter.

Regeneration is an event that occurs every 15 hours of engine normal operation. It is also known as "passive regeneration" and it works as follow: the DOC oxidizes a fraction of NO, produced by the engine, into NO_2. The nitrogen dioxide oxidizes the particulate collected on the DPF at low temperature (about 250/350 °C), lower than the oxygen would have required (about 550 °C). This mechanism allows to do the regeneration at lower temperatures and to avoid the post-injections used for the active regeneration. In this way the fuel penalty is eliminated.

The reactions required for the regeneration are the following:

$$\boldsymbol{DOC}: \quad 2NO + O_2 \overset{Pt}{\leftrightarrow} 2NO_2$$

$$\boldsymbol{DPF}: \quad C + 2NO_2 \rightarrow CO_2 + 2NO \quad (250°C \leq T \leq 350\,°C \; - \; passive\ regeneration)$$

$$\boldsymbol{DPF}: \quad C + O_2 \rightarrow CO_2 \; (T > 550°C - active\ regeneration)$$

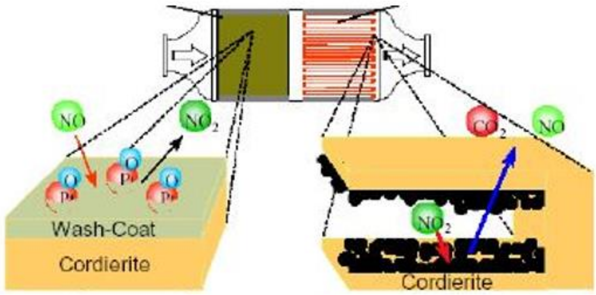

FIGURE 33 - DOC AND DPF *

A new content of the model year 2024 that improves the anti-particulate filter functionality is the so called "cleanability". The DPF coating is made in such a material to allow a better tolerance to mechanical cleanability. This ensure an easier filter restoration with respect to the previous models.

3) Selective Catalytic Reduction

The selective catalytic reduction (SCR) is a chemical process that is devoted to the reduction of nitrogen oxide emissions. The objective is to reduce nitrogen monoxide (NO) and nitrogen dioxide (NO_2) into pure nitrogen (N_2). This reduction can be obtained through the injection of a reducing agent in the exhaust gas stream before the catalyst: the ammonia (NH_3). This compound is obtained through the hydrolysis process of AdBlue®, a 32,5% aqueous solution of urea, and demineralized water at a temperature above 200°C.

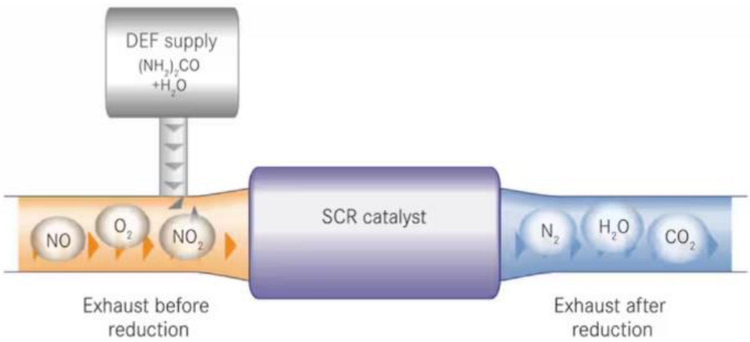

FIGURE 4 - EXHAUST GAS FLOW IN THE SCR

The urea solution is pumped from the urea tank and sprayed through an atomizing nozzle (Ad-Blue dosing module) into the exhaust gas stream. The mixing of urea (AdBlue® liquid) with exhaust gases and the formation of a uniform flow are very important in achieving high NO_x conversion. Disturbances in the flow may be minimized by avoiding sharp turns in the pipes and other physical obstacles upstream of the SCR catalyst.

Once mixed with the hot exhaust gas, the urea undergoes a hydrolysis reaction, producing ammonia. The hydrolysis reaction is the following:

$$(NH_3)_2CO + H_2O \rightarrow 2NH_3 + CO_2$$

The mixture of exhaust gases and ammonia gets in the SCR Catalyst where the reduction of nitrogen oxides in pure nitrogen occurs.

The SCR catalyst is made in a technology based on Titanium-Vanadium elements. This choice allows for smaller dimensions and enhanced performances of the system. In particular, the real advantage of this material combination is that it broads the temperature range in which the catalyst performs, decreasing the lower temperature threshold. In this way the propulsion system can comply with the cold start tests provided by the step E homologation requirements [23].

The reaction that may happen in the SCR are three:

(1) $$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

(2) $$2NH_3 + NO + NO_2 \rightarrow 2N_2 + 3H_2O$$

(3) $$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O$$

To ensure the reduction of the greatest amount of pollutants and to obtain an high conversion efficiency, the second reaction is the one to be promoted. This reaction requires an optimal ratio between NO_2 and NO. This may be obtained through a proper sizing of the diesel oxidation catalyst and with an opportune choice of precious metals.

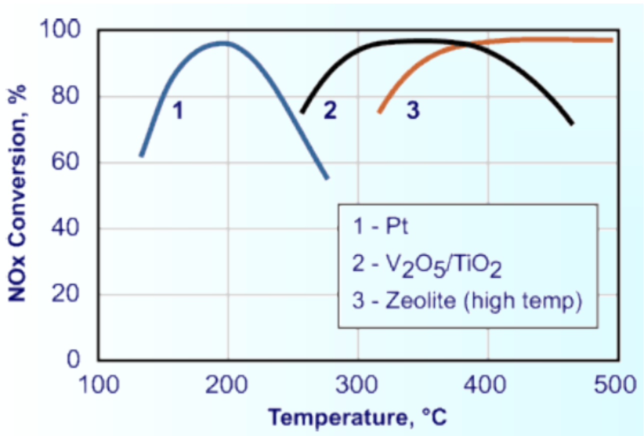

FIGURE 2.35 - NOX CONVERSION VS TEMPERATURE OF THREE SCR TECHNOLOGIES *

The checking of the NO_x conversion can be performed through two types of control: open loop and closed loop. In the open loop control, the management of NO_x emissions is performed controlling the combustion, the exhaust gas temperature, and the urea dosing independently from each other. In the closed loop control, on the contrary, the three previous controls are integrated to optimize the NO_x emissions management. The closed loop control provides better NO_x management in a wider range of operating conditions because it evaluates the amount of pollutant as an average on short term window basis. This means that engine-out NO_x emissions, as well as NH_3, are measured almost in real time, in a faster way than the open loop control [13].

Closed loop control allows to achieve a better NO_x conversion efficiency in critical operating conditions (e.g. aged ATS, cold operation). It allows to obtain more than 90% of conversion efficiency during high transient (for instance during transient test cycles). The use of closed loop system would also minimize the calibration work that is required for the development of open loop system. The main concern in designing closed loop systems is the lack of accurate, fast response NO_x and NH_3 sensors.

The most common in-site measurement technology relies on ZrO_2 – based electrochemical sensors that are similar to the oxygen-based sensors used for the three-way catalyst systems of spark ignition engines. For ammonia measurement, in-site laser light-based adsorption sensors are used.

4) Clean Up Catalyst

After the SCR system there could happen that a fraction of the NH_3 does not take part to the reduction reaction. This phenomenon is known as “ammonia slip” and it is controlled by the Clean Up Catalyst (CUC) placed right after the SCR. The residual ammonia is transformed into pure nitrogen and water through the following reaction:

$$4NH_3 + 3O_2 \rightarrow 2N_2 + 6\,H_2O$$

* The pictures are taken from the PowerPoint slides of the course of Engine Emission Control of Professor Federico Millo, Politecnico di Torino.

2.3 General considerations

When it comes to set up a new diesel engine, the most attractive emission strategy, when using a selective catalytic reducer, is to calibrate the engine to obtain low particulate matter (through a proper injection timing and high injection pressure) and using SCR catalyst to reduce the increased amount of NO_x. Depending on the severity of the emission standard, this approach was sufficient in the past, up to Euro V, to meet the PM emission limit of 0,02 g/kWh. For the current Euro VI the use of DPF has proved to be mandatory to reach the updated limit of 0,01 g/kWh and the introduction of a limit to the particulate number. Such low PM engine calibration leads, by contrast, to higher NO_x emissions. Depending on the engine calibration, a worst-case baseline NO_x of 7-8 g/kWh may be increased up to 9-11 g/kWh. For this reason, an urea-SCR after treatment system must be used to bring down the NO_x emissions to below 0,5 g/kWh.

In the past, in the FPT Industrial mindset, urea-SCR was considered more attractive, especially in the Heavy-Duty applications, than the competing EGR technology, which brought a fuel economy penalty. Urea-SCR also had a fuel economy advantage over lean NO_x adsorber catalysts due the fuel economy penalty during adsorber regeneration. One needs to remember, however, that fuel savings in propulsion systems with SCR are offsets by the cost of urea, which is consumed at about 3-5% of the fuel volume.

3. Product development process

In this chapter it will be briefly explained how a new engine is conceived, and which are the main phases that make up the physical development of a product. A few words will be then dedicated to the risk management of the company, and to some problem-solving techniques used to manage issues within project development. In the automotive world, the development of a product (that can be a generic vehicle or a vehicle's subsystem) is also called Product Development Process (abbreviated as PDP) and it describes a set of activities that go from the market and social trends understanding to the customer launch of the new product.

This case study focuses on the product category of an internal combustion engine of a truck. Generally, the product lines of the engines are classified according to the product family to which they belong. Each distinct engine is called a program. In this case the engine under investigation is a new program belonging to a specific engine family. What will be described hereafter is only a general indication of the process because this one is always customized by each OEM. Since PDP represents the way of the company to manage the product development programs, it constitutes part of the company expertise and know-how [25].

3.1 PDP overview and phases

The product development process is basically a set of activities, and related resources, that generate an output with the main scope of reaching customer satisfaction. The aim of PDP is to plan the whole product lifecycle, from the concept generation phase to the pre-mass production and production ramp up phase, as much as possible according to customer expectations.

Products can be considered new products (including new production site and first application), derived versions or minor application of existing products, existing products to be distributed in new markets, existing products manufactured in new plants.

According to the amount of new contents, the product complexity changes, and so also the activities that must be done in the development process (like the number of validations, number of material and parts sourcing, number of concept stages and so on). For this reason, the new programs can be classified accordingly, and they are associated to a specific size.

PDP is a structured approach to product and process design that enables OEM and suppliers to design a product that satisfies customer through a standardized set of quality requirements. It is the core process for many enterprises, and its application complies with the increasing need of designing products, processes, and production facilities overall integrated and globally optimized, under a long-term perspective.

The PDP is a management approach based on delivery. This means the necessity to define objectives and impose plans for the way to achieve them under constraints, and by a continuous activity of monitoring and controlling. These objectives are also called deliverables. A deliverable can be defined as a tangible result, like a feasibility study, a list of specifications, a product, that must be completed by a specified time [25].

The key drivers of the FPT industrial development process are:

- focus on time to market (TTM);
- customer experience integration;
- decision making approach.

Time to market is a really important factor for a company. It is defined as the time that elapses between the start of the development process of a new product and the start of its commercialization. A winning enterprise must reduce the TTM, in order to be more competitive and robust on the market. According to FPT Industrial, the reduction of TTM is achieved by the so called “phases overlapping”. It allows, after risk assessment evaluation, to start a development phase before the completion of the previous one.

The customer experience, instead, is secured by rigor on product conformance to the regulation, salability criteria, integration of logistics and aftermarket solutions since the early phases of development and accuracy in requirements and target deployment.

Finally, between the development phases, in key moments in the evolution of a project, there are explicit “decision points”. They are called management reviews and represent formal "ok to" proceed events. These meetings involve all the main company functions like product engineering, customer management, quality and so on.

In the following picture it is possible to see the main phases of the PDP.

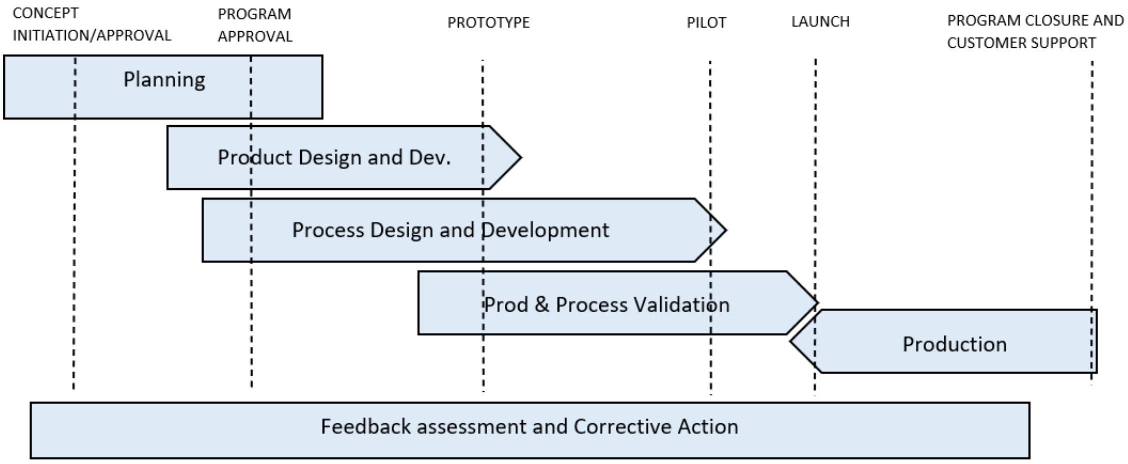

FIGURE 3.1 - PDP PHASES

A description of each phase is reported below.

Planning

In the planning phase all the activities of product planning are performed. This comprises a study of the market where the customer needs, wants, expectations and desires are analyzed. Then, to have a more objective view, all the information collected are translated into requirements that the product must fulfill. A list of preliminary special characteristics and design/reliability goals are also established. The project targets are reviewed and estimated in terms of technical and economic feasibility. According to the level of new content, the program sizing is specified.

Product and Process Design and Development

The product development phase starts with the concept selection. Here the possible new "concept" required to satisfy customer expectations, business strategic goals and market regulations is identified, selected, and confirmed. Product characteristics and technical specifications are evaluated, i.e. geometry, design features, details, and tolerance. All these aspects are revised in a formal design review.

For what the process development phase is concerned, it formalizes the translation of the information created during the product development phase into all the resources that will be applied to the manufacturing and assembly process. The resources are the production lines, tools, standard operational procedures and so on. Therefore, this phase establishes the passage from the design engineer's vision (the drawing) into reality (manufacturing process). As it is possible to notice, the two phases go in parallel, in coherence with the time-to-market optimization approach introduced before.

Product and Process Validation

This phase is constituted by a set of cycles of design - manufacturing - test that are iterated several times until the validation is reached. This apply both to the product and to the process. Before a vehicle can be introduced into commerce and sold, it must have a certificate of conformity and an approved fuel economy label. To do so, the engine must be correctly certified and labelled according to specific legal requirements. The certification process of a new engine rating should start at the beginning of FDP. It must finish before the start of the Pilot Stage and approximately it has a minimum lead-time of 9 to 18 months, depending to the country market of certification, the segment of the product (On-Road, Off-Road or Marine) and the grade of derivation of the new engine respect to existing versions (Program Sizing).

Suitable plans must be put in place to guarantee product compliance at the start of production and for the entire product lifecycle. Among these there are the so-called Conformity of Production (COP) and In-Service Conformity (ISC).

The validation of the product is done on the final design. The product performances in terms of functionality and durability are finalized with a "production intent" design. For this purpose, all the suppliers have to be selected and nominated. The validation of the process, instead, involves the process quality and the production volume capability. This is the phase where suppliers' process qualification is completed through process audit at suppliers' facilities and new machinery installation run-off at FPT plant is conducted.

Production

It is the phase where the start of production at FPT plant is approved. The terms and conditions of the relationship between the OEM and the suppliers is approved and all the related documentation is ready. This phase comprises the "Readiness to Launch" process. It tracks and confirms that the FPT product (Engine & ATS, Axles & Transmission), as a sub-system of the final vehicle/machine, has been successfully developed and industrialized and all the possible risks with impact on Customer Launch have been considered. The product is compliant with regulations, and it is ready to be ordered.

Feedback Assessment and Corrective Action

The whole process embraces a lean methodology that is based on a continuous improvement of processes and functions. To promote this improvement, it is necessary to increase customer satisfaction with every new product release. For this reason, it is required to capture feedback and learn from risks, issues and mistakes occurred in all phases of product development. The tool used for this purpose is the so-called Lesson Learned (abbreviated LL). These are formalized and documented solutions captured by all company functions involved in product development found to solve failures, to assess risks and after problem solving activities occurred in previous programs or from field. Technical learning from Product/Process Development should be captured to improve the company knowledge and to support future launches through, for example, update of design/testing norms or others technical standard or procedures [18].

3.2 Risk based model

Several times the word "risk" has been mentioned in this chapter. A risk is defined as an event (internal or external to the project) that may affect the project results in terms of time, cost, and quality. It can appear anytime during the project, and it is possible to estimate the probability of occurrence.

The risks to which a company may be exposed are several. Them are:

- financial and operational risks (capital investments, industry geographical area, market segment);
- market risks (exchange rate, interest rate, price trends of raw material, goods or services);
- hazard risks (physical damages, production stop etc.);
- innovation risks (manufacturing process inefficiencies, etc.);
- technological risks (product or technology reliability)
- competencies and human resources related risks (lack or inadequacies of available competencies).

The sources of risk can be:

- changes in product requirements;
- mistakes during the design phase, lacks, misunderstanding;
- poor definition of project roles and responsibilities;
- not precise estimation of resources, time, and cost;
- inadequacy of project team competencies.

Risk management is a must because each project is, by definition, a complex, temporary innovative, cross-functional, and therefore unique effort to solve a defined problem. According to risk management, a risk can be managed if the risk exposure (the loss or the damage) can be evaluated (better if economically) and if it is possible to manage it through the planning of appropriate recovery actions. If one of these conditions is not satisfied, the risk simply becomes a constraint that must be accepted. It may happen that a risk has a positive impact on the project. In this case the risk is called "opportunity".

The objective of risk management is to identify project risks and to develop appropriate strategies so to significantly reduce their number and their effect, to actuate actions in order to avoid them and, at the same time, to maximize the related opportunities.

To manage project risk means therefore to collect and evaluate, according to the most objective metric as possible, each possible technical, market, or management risk applicable to the project in order to establish recovery plans to avoid their reoccurrence or to mitigate their negative effects [26].

The product development process adopted by FPT implements a “risk-based” decision model. This means that for every process mapped within the PDP it is required to identify the risks (and related opportunities) that are relevant for the company.

3.2.1 Risk management process

The following picture depicts the ideal process of risk management.

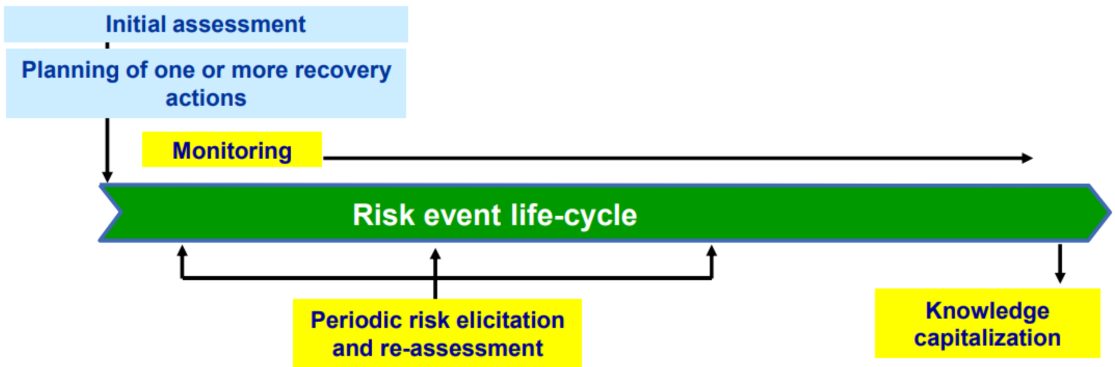

FIGURE 3.2 - PROCESS OF RISK MANAGEMENT *

The first activity to do is the identification of the risk events. In this preliminary phase, the threats and the opportunities that can be foreseen during the real development of the project must be identified. Having found the risks, they must be evaluated. The risk level can be measured in terms of probability of occurrence, magnitude of loss (gravity), and capability to solve or reduce the risk (control).

After the risk ranking, the phase of risk treatment can start. Based on the results achieved during the evaluation phase, all risk events are arranged according to the corresponding priority set by the risk level. Starting from the highest priorities, for each risk event one or more recovery actions must be identified, assigned to identified roles and planned into a timetable.

The effectiveness of the recovery action is then monitored and assessed. On the market, many software tools are available to support process modelling, risk event identification, risk event evaluation, and alternative scenario simulation.

At the end of the risk management process it follows knowledge capitalization, in which the best practices are collected, and the technical lessons are captured and stored, with the main goal to improve the company processes and knowledge [26].

* Picture taken from the PowerPoint slides of the course of Project Management and Cost Value Analysis of Professor Cesare Volante, Politecnico di Torino.

3.3 Problem solving

The problem-solving stage can be defined as a process that apply generic or ad hoc methods, in an orderly manner, for finding solutions to the problems.

The technical problem solving, which is applied mainly in industry, does not differ significantly in its nature from problem solving in other areas, although there are some very specific methods, which will be briefly explained later in this subchapter.

Since technical problem solving can quickly become very complex and difficult, and sometimes involve extremely high costs, systematic processing is even more important.

A first approach to very complex problems is to “cut the elephant to pieces”. This means that the problem is broken down into smaller packages (subproblems) and so made more manageable. Initially, the task can seem big, complex, and overwhelming. But when you divide it into smaller packages, it becomes a solvable challenge.

The further systematic approach to problem-solving is shown schematically in the following figure. This is the so-called problem-solving funnel designed to illustrate the process.

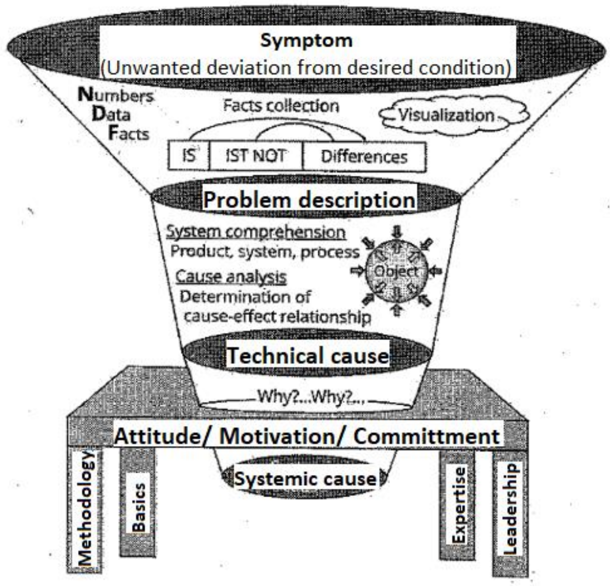

FIGURE 3.3 - PROBLEM-SOLVING FUNNEL *

Here, the funnel is connected to a table, which symbolizes, with its legs and the tabletop, the basic requirements for problem-solving.

Before explaining the main layers of the funnel, a look at the construction underneath is needed. Like a real table, problem-solving needs a stable basis. On one hand, this basis is represented by the table legs, which symbolize the methodology, the basics, the expertise, and the leadership. These points include the knowledge and skills that are required for solving problems. On the other hand, the tabletop stands for the attitude of the problem-solver, his motivation and commitment, but also the objectivity and the openness to approach problems. If one leg of the table is taken away, the whole table falls over. This is equivalent to the failure of the problem-solving approach. All the above-listed factors contribute to a stable basis and are necessary components of a good problem solution [27].

* Picture taken from the book "Problem Solving: A systematic approach to solving problems" written by Dr. Oliver Friedrichs and published by Tredition.

3.3.1 Problem description

Now, entering on the actual funnel, the first part of problem-solving is represented by the "Problem description" phase. It focuses on identifying the fundamental problem. Starting from the observed symptoms, the problem is described in detail by determining the differences between what is "good" and "bad" (or between "problem" and "no problem"). The difficulties in this part are mainly to collect meaningful and reliable information that allows you to achieve the task. A clear separation of the basic problem from the resultant effects, the symptoms, is very important.

A good help for the problem description phase comes from the questions known as wh-questions, that are the following:

- What exactly is (not) the problem?
- Where exactly is the problem (not) observed?
- When exactly is the problem (not) observed?
- How often does the problem (not) occur? How much is (not) affected?

Of particular importance is the question regarding "is not". This allows the problem solver to prevent confirmation bias on one hand, and on the other hand, it is possible to assess information that is usually difficult to consider. An absence is usually much harder to grasp than something directly present.

After the crucial differences have been identified, the actual problem can be formulated. The problem description is a concise fact-based description of the underlying problem. It is fundamental to rely at this point as much as possible only on facts. So, the problem description phase can be also defined as a collection of facts [27].

3.3.2 Determination of causes

While the previous part deals with the problem, the second part focuses on the causes. This implies the formulation of hypotheses of the potential causes of the problem considered. Nevertheless, before engaging in the discussion of hypotheses, it is important to achieve a common understanding of the underlying system. This step is so important, because it is difficult to definitively eliminate a problem without sufficiently understanding it. Without sufficient technical understanding, one may run the risk of implementing inadequate solutions or measures that lead to even greater problems. For this reason, it is needed to define the internal and external parameters and processes involved in the failure.

External parameters are the environmental influence (wind, temperature, humidity, etc.), as well as the influence of the ambient system (vibrations of other components, special installation situation, etc.). The internal parameters, instead, focus on the design of the product and the ability of the manufacturing process. Properties such as geometry and strength, as well as manufacturing tolerances are decisive here. Both external and internal parameters are important to an overall view that includes the evaluation of processes, systems, and components.

If the necessary understanding of the system is available, the technical causes can be determined. A very useful method to do that can be the cause-effect or Ishikawa diagram, represented in the following picture.

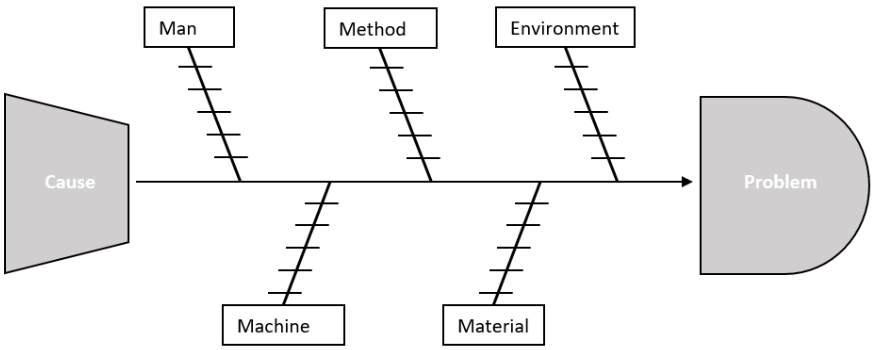

FIGURE 3.4 – ISHIKAWA DIAGRAM

This diagram attempt to trace systematically the fundamental problem back to the possible causes, assigned to different categories (man, method, environment, machine, material). It is important here to start not from the initially observed symptoms, but from the underlying problem. Indeed, starting from the symptoms, the Ishikawa diagram would quickly start to become large and confusing, and a lot of effort and time would be required in clarifying each single points. If, on the other hand, a detailed description of the problem has been done, many of these points do not need to be considered anymore. In this case, the Ishikawa diagram might just be used as a control tool to ensure that nothing has been forgotten in the discussion.

Once the technical causes have been determined and verified, it is necessary to find also the managerial or systemic causes, that comes from organizational or leadership inconsistencies. This point is very delicate and constructive solutions have to be found without pointing fingers. The goal is to find together with the management a common solution or improvement.

Therefore, a method can be applied, and this is the so-called “5 x Why”, which is a very important and central problem-solving method. Based on the previously identified technical causes, one tries to find the managerial causes by repeatedly asking the question “Why?”. In the end, a logical chain is formed in which both the technical and the systemic causes emerge. In the chain, assumptions must be avoided and only verified findings are to be used. A simple example of the “5 x Why” is shown on the following picture.

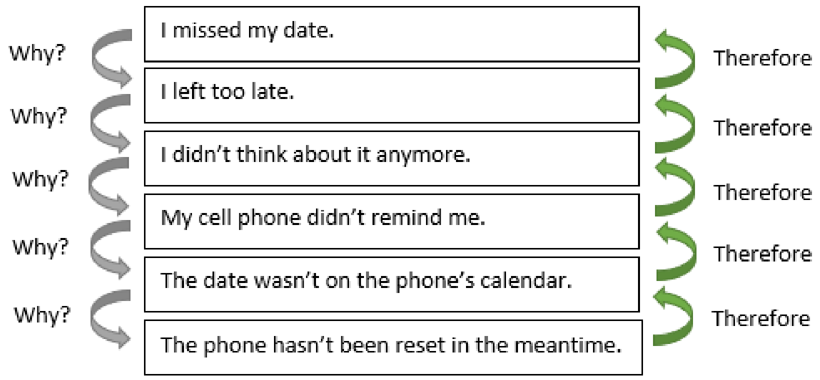

FIGURE 3.5 - EXAMPLE OF "5 X WHY"

The logical chain of “Why” questions can be checked by starting from the back of it and connecting the answers with “therefore”. In this way another logical chain is created, that will allow people to check quickly for logic breaks in the argumentation [27].

3.3.3 Implementation of sustainable solutions

The problem-solving funnel from Figure 2 presents only the problem description and the determination of technical and managerial causes. It is necessary then, to ensure for the future, that the problems and causes previously found are permanently eliminated. The key points that must be achieved are the following:

- Implementation of sustainable measures
- Documentation of results
- Dissemination of knowledge

The implementation of sustainable measures has the aim of preventing future occurrence of the problem. The documentation of results is useful to create knowledge that can be used for future problem solving and prevention. By providing information to relevant target groups, similar future problems can be avoided, and analysis already executed are not repeated.

It is important that the information obtained are accessible by relevant target groups. This is generally done by storing the information in databases, but also by informing directly relevant employees or departments [27].

3.3.4 8D methodology

In 1974, the US Department of Defense developed and standardized a problem-solving method called 8D. This method is considered the basis of the problem-solving approach previously described and represents the scheme for a systematic problem solution.

The 8D methodology is made by the following phases:

D1:Establishing problem-solving team
D2:Problem description
D3:Containment action
D4:Cause and effect analysis
D5:Defining corrective actions and providing effectiveness
D6:Implementing corrective actions and tracking effectiveness
D7:Establishing preventive actions
D8:Final meeting

The first step of the 8D method (step D1) is to establish the problem-solving team and project. Here the goals and the necessary resources are defined.

After this has been clarified, the problem is described in detail (step D2). In addition to this, an initial risk assessment regarding consequences to the customer is performed.

Depending on the risk, sometimes it happens that immediate measures have to be taken (step D3) at a very early stage to protect the customer. For example, it can be a delivery stop or a complete visual inspection of the parts to be shipped. Generally, the actual causes of the issue are still unclear.

In step D4, the cause-effect analysis is carried out. Here the technical and systemic causes are investigated. After these are found, identification and verification of the causes is done.

Step D5 and D6 deal with the definition and the implementation of corrective actions. Once the effectiveness of the action has been demonstrated, a full implementation is done. Here the effectiveness of the measures is carefully monitored. After the implementation, a risk has to be assessed and it should be significantly lower than the risk before the implementation of the measures. If the corrective actions have successfully applied, the containment measure can be revoked.

In step D7, to ensure the success of the solution, preventive measures are taken. This is also referred as “Lessons Learned”. On the one hand, these preventive measures can be processing changes that exclude the problem in the future. On the other hand, they can also consist of new knowledge gained from the problem-solving process, which is documented and registered.

Last but not least, step D8 set the termination of the problem-solving “process”, which usually happens at a final meeting. The aim is to evaluate the project process with the team and to check if the established goals have been achieved. An often underestimated point is to appreciate the work and the dedication of the team. This is important for motivating employees to handle further cases [27].

3.3.5 Other problem-solving methods

In technical problem-solving approach, there are many different, complementary methods. Depending on the application, they contribute significantly to problem-solving with their own characteristic features. However, they all have in common the fact that they largely follow the basic structure of the previously described 8D method.

Some of the most common methods used to solve the problem are the following:

- Shainin
- Six Sigma
- Toyota Production System
- Kaizen

The root cause analysis of Shainin is a pragmatic way to locate and quickly identify causes. Unlike other approaches, the Shainin method try to deduce the actual cause from the result that shows the problem. You look for the extremely bad (WOW: worst of worst) and the extremely good (BOB: best of best) products or processes. Based on the differences between BOB and WOW, the causes are determined using various strategies [27].

Six Sigma (6σ) is a management system for process improvement, statistical quality goals, and, at the same time, a method of quality management. Its core element is the description, measurement, analysis, improvement, and monitoring of business transactions by statistical means [27].

Toyota Production System uses a very effective even if not well-known tool, called 5G. Unless the others, that are purely root cause analysis methods, 5G is more an approach. Indeed, it gives useful indications and set a behavior for companies that pursue lean manufacturing and aiming to waste reduction. In the following figure the main 5 indications of this innovative approach are listed.

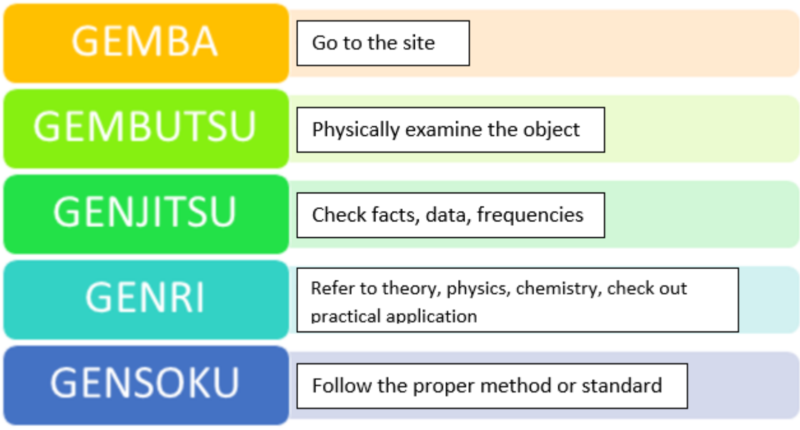

FIGURE 3.6 - 5G OF TOYOTA PRODUCTION SYSTEM

Kaizen is a Japanese word that stands for “continuous improvement”. It refers to activities that continuously improve processes and functions, involves all the people of the company, and it is aimed to eliminate waste. The practical implementation of Kaizen is performed through the so called PDCA cycle, which represents more than a simple problem-solving tool. Indeed Kaizen, thanks to its logic, lends itself as an instrument of extended engagement of people in the solutions finding, and it represents an effective tool in the development of a hint system [28].

4. Bench test facilities

A test bench is a set of equipment installed in a room generally tempered and ventilated. It can be very simple in the case of elementary engine function test, or very complex in the case of simulation of real operation of a powertrain or a complete vehicle. In this case study, the focus has been centered on the engine benches and the related components and instrumentation.

The services provided on test benches can have several objectives:

- Development: that are activities of fine-tuning, calibration of engine control systems, qualification of the performance of components or complete engines;
- Approval or validation: this comprises normative aspects, thus the activities of verification that the engine meets pollution standards and specifications in terms of consumption and power;
- Validation and control: qualification of powertrain or organ endurance, accelerated ageing tests, reliability tests, specific endurance cycles.

In the following picture are listed all the measurements that can be done:

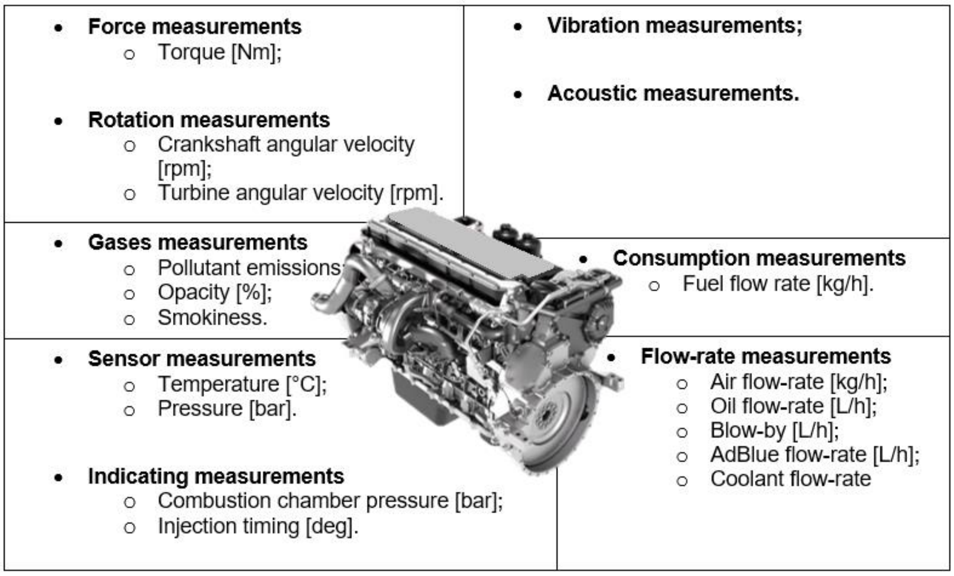

FIGURE 4.1 - ENGINE BENCH TEST MEASUREMENTS

The measurements related to the torque, fuel consumption and pollutant emissions are related to the engine performance. It is possible to evaluate how they evolve varying the engine regulation parameters and therefore to optimize them (engine map tuning). Still in the field of performance, the engine bench tests can evaluate the engine behavior during load transient cycles and at constant load, at the typical engine speeds during the vehicle usage [29].

At this point it is useful to distinguish between the dynamic test cells and the steady-state test cells. The first ones are equipped with devices able to simulate the typical vehicle's behavior by applying variable loads to the engine. The steady-state ones, instead, work in opposition to the previous ones, because they maintain the engine at fixed operating points (fixed engine speeds) independently from the applied load. In addition to this, engine reliability demonstrations can be done performing the durability tests.

4.1 Bench test facilities at FPT Industrial

The engine testing centers of FPT Industrial are distributed over four countries across the world. Two in Italy: one in Foggia, specialized in natural gas engines and one in Turin, devoted to diesel engines. In Arbon, Switzerland, there is an important research and development center that has bench test focused on advanced technologies comprising hydrogen fueled engines. Other testing facilities are present also in Burr Ridge, North America and Contagem, Latin America. The focus is on the industrial site of Turin. In the Italian testing facilities of Northern Italy there are about fifty motor cells and fifty cells dedicated to the test of drivelines (comprising axles, e-axles, and e-motors).

There are also special testing cells called "tilting" where the engine can be assembled and tilted about both longitudinal and transversal axes (45° degrees on the single axis and about 30° when combined). These cells verify that in the tilted engine, the coolant, and the lubricant flow correctly and the filtration capacity of blow-by gases remains acceptable.

Other benches are the semi anechoic, the climatic and the barometric cells. The first one is a completely soundproofed cell that is used for noise, harshness, and vibrations analysis; the climatic and the barometric cells are used to make cold tests and high-altitude simulations (up to 4000 meters above sea level). The typical tests conducted here are the so called “startability”, where the correct cranking of the engine in harsh environment is verified, and verification of the capability of the engine to keep the operating oil pressure.

4.2 Cell layout and components

The test cells are rooms composed by a collection of installation that are listed below:

- *Dynamometer brake:* it regulates and measure the engine torque in a prefixed range;
- *Fuel supply system:* it guarantees the fuel supply to the internal combustion engine;
- *Electrical system:* it guarantees the electricity supply to the engine and to the test cell;
- *Air system:* it provides combustion air to the engine at intake level, cooling air to the engine itself, air conditioning to the room, and it guarantees the exhaust gases extraction;
- *MRU:* it stands for measurement, regulation, and control units. It’s the test cell instrumentation and software interface that guarantees the engine control;
- *Data acquisition system:* instrumentation apt to acquire engine function data;
- *Security system:* it is a series of devices that check the test cell environment and the security of the equipment for the operator’s health.

To set up the internal combustion engine in the cell it is necessary to connect the cables into an interface that allows to control the engine functions from outside (for instance the accelerator). In the following picture there is the scheme that explains how to connect sensors and cables.

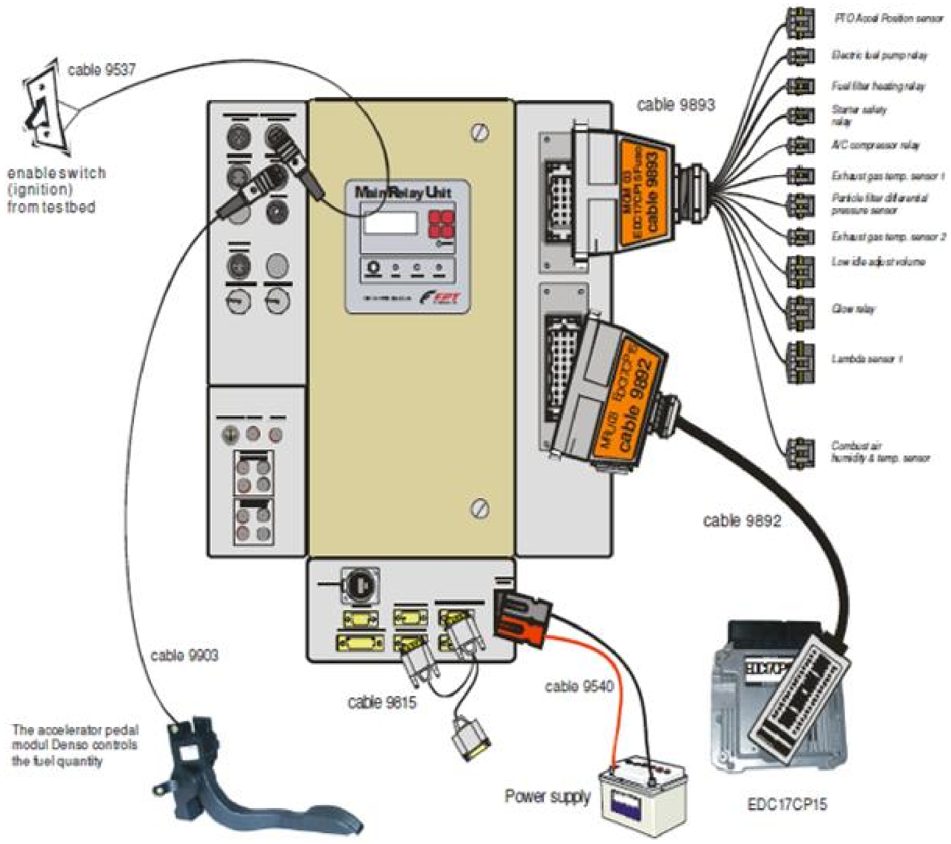

FIGURE 4.2 - SCHEME OF ENGINE SENSORS AND CONTROL CONNECTION

During the testing activities on the bench, an automated system acquires all the data from the sensors (pressures, temperatures, fuel consumption etc.). The system also captures the parameters of the ECU and the minimum and maximum alarm limits. About the latter, in case of limit exceedance, the automated system immediately stops the test and makes available to the database of a central control unit the last minutes data of the engine test.

The centralized control unit receives all the data acquired by the sensors with a resolution of one second. These data can be consulted and elaborated for the test conclusions by the operators of the "post-processing" company division.

In the following picture it is shown the controls and the dashboard of the test bench cell automated system.

FIGURE 4.3 - DASHBOARD AND CONTROLS OF THE TEST BENCH CELL

The automated system of the test cell used for the homologation is supplied by AVL. Other systems used in the test cell are the PSS-20, which is a particulate sampling system for particulate number measurement and the FTIR, used to measure the ammonia concentration. The software "INCA" works interacting with the engine control unit.

4.3 Physical parameters and measuring tools

The physical quantities measured in a test cell are made through a measurement chain. This term chain indicates a set of stages of a measuring instrument, which process the information detected by the physical quantity object of study, to then present a result. The main stages of a measurement chain are three:

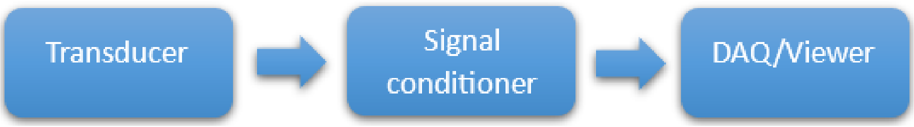

FIGURE 4.4 - MEASUREMENT CHAIN

The first stage consists of a sensor and/or a transducer in contact with the physical quantity to be detected. The second stage consists of an intermediate signal processing system or signal conditioner which converts the information coming from the previous stages into a form such as adapting to the acquisition system. These operations include noise filtering, linearization of transfer functions, conversion, and amplification of the signal produced by the transducer. The third stage is represented by the terminal instrument which indicates the result of the operations carried out by the previous stages, showing it to the operator.

In a measurement procedure there is a distinction between the measured value and the true value. The difference between them is called error. The error depends both on the instrument and the observer. There are two main types of errors:

- Random errors (which may vary from one observer to another);
- Systematic errors (which always occurs, with the same value, when the instrument is used in the same way and in the same case).

The quality of the measurement result, its accuracy, is characterized by uncertainty, which defines an interval around the measured value, where the true value lies with some probability. Measurement uncertainty can be regarded as an estimate, what is the highest probable absolute difference between the measured value and the true value. If uncertainty estimate is obtained from statistical treatment of repeated measurement results, then it is called A-type estimate. On the contrary, if the uncertainty estimate is not obtained using repeated measurements, it’s called B type.

For the first one, the treatment is usually a calculation of the standard deviation. It is calculated as follows:

$$u(x) = \sqrt{\frac{\sum_{i=n}^{n}(x_i - \bar{x})^2}{n-1}}$$

For the B type ones the calculation method is the rectangular distribution model. It is identified through two values $x_{i,\,min}$ and $x_{i,\,max}$. Inside the rectangular range, all values have the same probability. It is calculated as follows:

$$u(\bar{x}_i) = \frac{x_{i,max} - x_{i,min}}{2\sqrt{3}}$$

For each measurement chain it must be guaranteed an uncertainty measurement value. This value is associated to the result of a measurement and characterizes the value dispersion of a result. The measurement chains are calibrated periodically through a simulator or dedicated generators. For this purpose, three factors are considered: the maximum error detected from measurements; the uncertainty of the sampling instrument used for the measurement; the resolution of the instrument [30].

4.3.1 Force measurement: torque

The torque measurement is performed with the use of a device that applies braking force. The device is a dynamometer, and it is installed inside the cell. The dynamometer brake allows to execute automatic cycles, including torque and speed ramps. It simulates the road load, and it can generate electrical power. It can perform all types of cycles: ETC, ESC, NTE, WHTC, WHSC, NRTC, NRSC, and FTP. So, both steady-state and transient cycles.

The dynamic brake is an AC motor that is represented in the following picture:

FIGURE 4.5 - DYNAMOMETER BRAKE

It can work as follow:

- Since the dyno is an electric motor, it can be used as generator;

- The mechanical energy produced by the generator is converted into electricity that is given to the grid through a special converter;
- The internal combustion engine can be dragged by the AC motor at speeds higher than its structural limits.

The braking system is here shown more in detail.

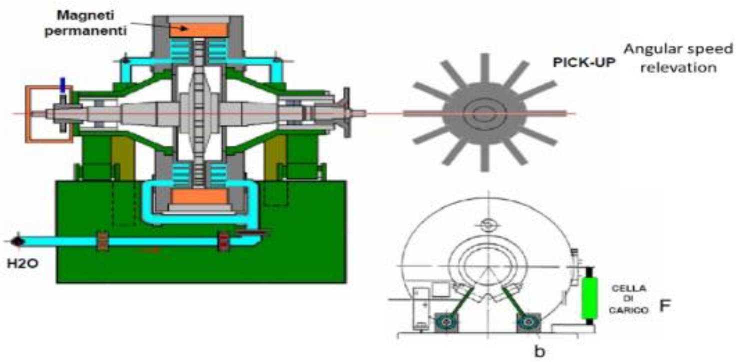

FIGURE 4.6 - TEST BENCH BRAKING SYSTEM

The first parameter to be computed is the torque M_t:

$$M_t[Nm] = F\ [N] \cdot b\ [m]$$

The engine power is obtained using the torque and the engine speed, detected by the pick-up gear.

$$P[W] = M_t[Nm] \cdot 2\pi\, n \left[\frac{\frac{giri}{min}}{60}\right]$$

$$P[CV] = F[N]\ \cdot b[m] \cdot 2\pi\, n \left[\frac{\frac{giri}{min}}{60 \cdot 75}\right]$$

$$P[CV] = F[N] \cdot \frac{b[m]}{716{,}2} \cdot n \left[\frac{giri}{min}\right]$$

Where:

- F is the force;

- b is the arm length of the load cell;
- n is the engine speed.

The power computed analytically is multiplied for a corrective factor, to consider environmental standard conditions. This is a method that allows to compare the engine performances in different ambient conditions. The torque is measured using a so called “torque flange”. It is a specialized device used for in-line torque measurement in power test stands. It is compact and short, and it is based on strain gage technology. The flanges are designed to measure torque directly on a shaft or flange. Their primary purpose is to accurately determine the torque being applied to a rotating shaft or component.

In the following picture the device is shown:

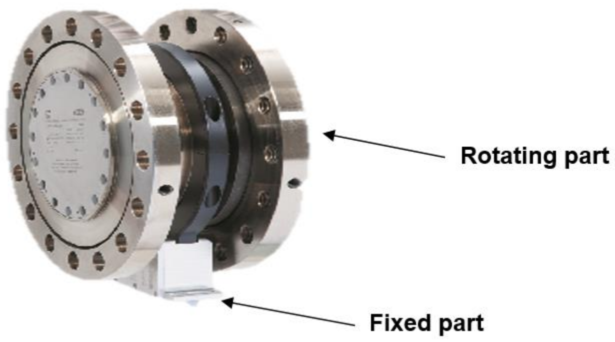

FIGURE 4.7 - TORQUE FLANGE

It is made by two main parts: a rotating part, where strain gauges, connected in full bridge, are mounted and a fixed part (the receiver). Torque flanges operate based on the strain gage principle. When torque is applied to the flange, it creates a twisting angle (torsion) in the material. The strain gages embedded in the flange detect this deformation and convert it into an electrical signal, as a variable frequency proportional to the measured torque. The frequency signal is then converted into a voltage signal from 0 to 10 V and acquired from the automation system the test cell. The gauging torque flange must be calibrated to ensure reliability in the measurement process. The calibration is done fixing the rotating part and mounting an arm with known length, where some weights are applied.

4.2.2 Rotation measurement

The measurement of rotation is usually performed through a so called “toothed tone ring”. It is a ferromagnetic toothed reluctor ring, just called tone ring, and a sensor element, constituted of a permanent magnet core surrounded by a coil.

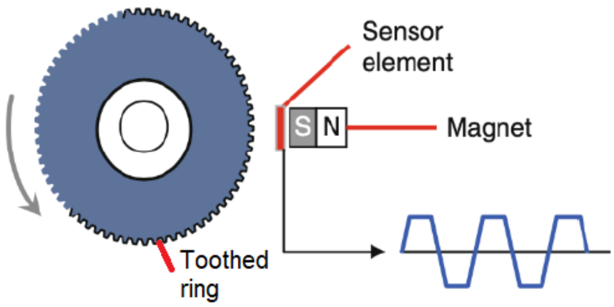

FIGURE 4.8 – TOOTHED TONE RING

The operational concept of the passive setup for this sensor is quite straightforward because it relies on the changeable reluctance between the sensor and the tone ring. When the reluctor ring rotates, it changes the magnetic field between the notch and the tooth, leading to the production of an alternating voltage in the coil. This voltage signal rises in frequency as the reluctor ring's speed increases. The result is an analog signal that necessitates conversion to digital for further processing.

4.2.3 Temperature measurement

Temperature measurement in the automotive industry is performed using a variety of sensors and techniques, depending on the specific application and requirements. The most common way is the use of thermal sensors. In this category there are thermocouples, resistance temperature detectors (RTDs), and thermistors. A brief overview of these sensors is the following.

1. Thermocouples

Thermocouples are widely used for temperature measurement in automotive applications due to their simplicity, durability, and wide temperature range (-100 to 1250°C). These sensors consist of two different metal wires joined at one end (called hot end). The other two ends are called “reference” or “cold” end. When there is a temperature difference between hot and cold ends, they generate a voltage, called Setback voltage, that is proportional to the temperature difference.

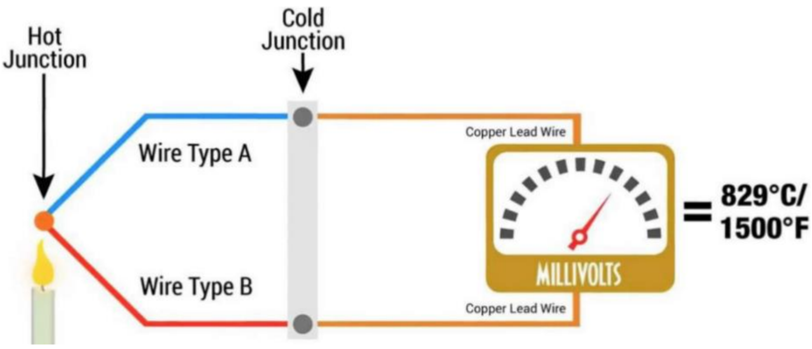

FIGURE 4.9 - THERMOCOUPLE SENSOR

2. Resistance temperature detector

RTDs are another common choice for temperature measurement in automotive systems. RTDs utilize the principle of resistivity change with temperature. They are simply piece of metal wire that have a known resistance at 0°C. The resistance value rises when the temperature increases, and this change in resistance is described by the following linear equation:

$$R = 0{,}385\ \frac{\Omega}{°C} \cdot T + 100\Omega$$

Where R is the resistance and T is the temperature. Solved for T, it becomes:

$$T = 2{,}597\ \frac{°C}{\Omega} \cdot R - 259{,}7°C$$

They offer high accuracy and stability over a wide temperature range. There are different materials available for such sensors like platinum, copper, or nickel. The platinum ones are more reliable since the behavior is more linear. There are three types of connection: with two, three, and four wires.

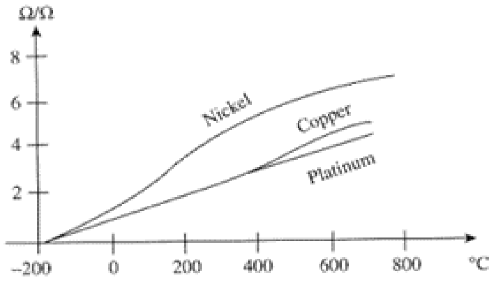

FIGURE 4.10 - RTD MATERIALS

3. Thermistors

Thermistors are temperature-sensitive resistors that change their resistance in response to temperature variations They are used to measure coolant temperature, intake air temperature, and cabin temperature due to their small size, fast response time, and low cost.

4.2.4 Pressure measurement

Pressure sensors are devices used to measure the pressure of gases or liquids in various industrial, commercial, and automotive applications. There are several types of pressure sensor but the most common are piezoelectric and piezoresistive ones.

1. Piezoelectric sensors

Piezoelectric pressure sensors utilizes the piezoelectric effect to measure the pressure. The piezoelectric effect refers to the generation of an electrical charge in certain materials when subjected to mechanical stress or pressure. These materials are called piezoelectric materials, and they typically rely on crystals such as quartz or a ceramic like lead zirconate titanate (PZT).

The crystal is sandwiched between two electrodes. As pressure is applied to the sensor, the piezoelectric material experiences deformation or strain, causing positive and negative charges to accumulate on opposite surfaces of the material. This charge separation results in an electric potential difference across the electrodes (V_{out}).

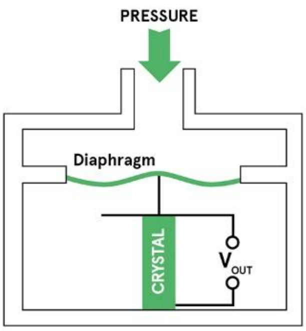

FIGURE 4.11 - PIEZOELECTRIC SENSOR

The generated voltage is directly proportional to the applied pressure. By measuring the voltage output of the sensor, the pressure can be determined. The voltage output from the electrodes may be very small and require amplification and conditioning before it can be used for measurement. The Piezoelectric pressure sensor allows to measure dynamic pressures at a temperature up to 500 °C. It is used to detect combustion chamber pressure.

2. Piezoresistive sensors

Piezoresistive sensors are commonly used due to their high sensitivity, accuracy, and reliability. These sensors employ a semiconductor material (such as silicon) that changes its resistance in response to applied pressure. When pressure is applied to a diaphragm containing piezoresistive elements, the resistance changes, which can be measured to determine the pressure.

FIGURE 4.12 - PIEZORESISTIVE PRESSURE SENSOR

This output signal can be either a current or a voltage, and it is measured with an accurate linearization. The voltage signals (from 0 to 10 V) are affected by the electromagnetic fields (shielded cables are used) and by the length of the connectors.

The Piezoresistive pressure sensors allows to measure static and dynamic pressures at a temperature up to 120 °C. These sensors are used to make measurements in remote positions.

4.2.5 Indicating measurement

In an internal combustion engine, several key metrics are crucial for assessing performance, efficiency, and overall health. These metrics are monitored to optimize engine function and diagnose issues. Commonly used indicators include:

1) crankshaft Position and Speed: Monitoring the crankshaft's position and speed provides insights into engine speed (RPM) and timing events. Sensors typically consist of a magnet and a Hall effect sensor near a toothed wheel on the crankshaft, which detects changes in the magnetic field to determine position and speed;
2) fuel Injection Timing and Quantity: Tracking fuel injection timing and quantity is vital for optimizing fuel delivery and combustion efficiency. Sensors like fuel injectors, pressure sensors, and flow meters measure and control these parameters.

4.2.6 Fuel consumption measurement

In an engine test bench cell, fuel consumption measurement is typically performed by integrating fuel flow measurement with data on the engine's operating time. Fuel flow measurement is performed using a fuel flow meter. This device, calibrated for accuracy, is installed in the fuel line to measure the rate of fuel flow in kilograms per hour (kg/h) or liters per hour (l/h), depending on the specific setup.

Concurrently, the test bench cell records the operating time of the engine. This can be done using various methods such as timers, engine control units (ECUs), or data acquisition systems that track the engine's runtime. The fuel flow rate (kg/h or l/h) measured by the flow meter is multiplied by the total operating time of the engine to calculate the total fuel consumption during the test period. For example, if the engine operates for 10 hours and the average fuel flow rate measured by the flow meter is 20 kg/h, then the total fuel consumption would be 200 kg:

$$10\ hours\ \cdot 20\ \frac{kg}{h} = 200\ kg$$

The device used for measuring fuel consumption is called PLU 121 and it is supplied by AVL. PLU is a commercial name (Precision Liquid Unit) and represents an high-precision measurement principle used in AVL fuel mass flow system for accurate fuel consumption measurement during engine testing and development. This technology ensures precise data quality and compliance with standards while assessing fuel consumption.

4.2.7 Air flow rate measurement

The air flow rate is measured through the “Mobile Intake air Measurement System (MIMS12)”, that measures the laminar flow. It is a crucial tool in the field of engine performance and emissions analysis. It allows for accurate measurement of the mass flow rate of air entering the engine, which directly impacts combustion efficiency, emissions, and overall engine health. It provides real-time information on the air intake, allowing for precise control and optimization of engine performance. The system is composed by:

- A laminar flow element;
- An air mass flow calculator DFR 10;
- An air mass flow calculator sensor box DFRS 10;
- An humidity and temperature transmitter;
- The PT10 temperature sensor;
- A remote tare and status box (switch).

In the following picture MIMS 12 components scheme is depicted:

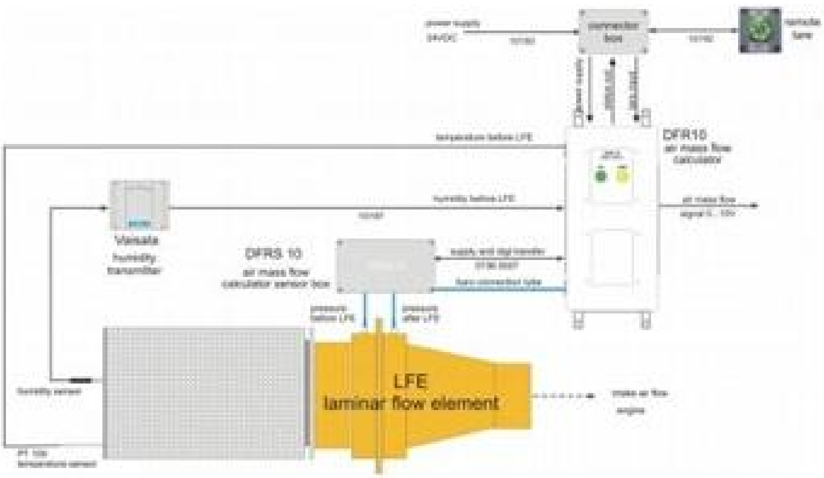

FIGURE 4.13 - MIMS 12 COMPONENTS

The system undergoes calibration following a sufficient thermal stabilization period of the unit under test (UUT) within the laboratory environment. To mitigate running-in influences, the UUT is operated for a minimum of 10 minutes at maximum flow before measurements are taken. Absolute pressure (PAp), temperature (Tp), and humidity (Hp) readings are obtained at the UUT entrance. The actual volume flow (Qvol) at the UUT entrance is derived from reference volume flow rates.

Evaluation is conducted through a Reynolds number transformation utilizing the Uniflow Polynomial:

$$Q = \left(P_n \cdot \left(\left(\frac{d \cdot \rho \cdot PX}{\eta^2}\right)^n + \ldots + P_1 \cdot \left(\frac{d \cdot \rho \cdot PX}{\eta^2}\right)\right)\right) \cdot \frac{\eta}{\rho \cdot PY}$$

Where:

- η is the dynamic viscosity ETA in Pa s;
- ρ is the density RHO in Kg/m^3.

4.3 Exhaust gas sampling and the analyzers

The “approval”, in the context of an homologation, refers to the process of certifying or confirming that a product meets the regulatory or technical standards set forth by relevant authorities or governing bodies. In particular, the approval of an engine means the approval of an engine regarding the level of emission of gaseous and particulate pollutants, smoke, and On-Board Diagnostic (OBD) system. For this reason, in addition to the measurement of the engine characteristics (performances, torque, and power), it is also requested to analyze the exhaust gases, to certify that the engine and ATS meet the current emission regulations.

Exhaust gas analysis can be conducted using different methods, such as sampling gases in bags, employing the so called “Constant Volume Sampling” (CVS), or directly sampling from the exhaust pipe.

With CVS, the exhaust gas flow rate remains constant as it is diluted by air. In this way, the risk of water vapor condensation in the sampling and measurement system is reduced. Condensed water has an undesired effect because it could carry pollutants, and it can distort the measurements. By the addition of the proper amount of dilution air, the water vapor pressure decreases, inhibiting condensation and minimizing pollutant reaction. Before the exhaust gases dilution, it is important to avoid the humidity condensation, because in this way the risk of removing soluble pollutants or interferences with NOx measurement are avoided.

The dew point of undiluted gas is around 49-54 °C, so it is crucial to ensure that exhaust gas temperature does not reach these levels before dilution. Dilution reduces pollutant concentration proportionally to the dilution ratio, requiring analyzers to be more sensitive. About the dilution ratio, it is the ratio between the volume of gases that flows through the sampling system and the volume of exhaust gases that get out from the engine during the test. It is calculated in standard environmental conditions and generally it is equal to 10.

In this case study, the exhaust gases sampling is done at the exhaust pipe level, right after the after-treatment system. This means that the raw exhaust gases are directly sent to the analyzers. The only case when a CVS is implied is for the particulate matter measurement. In that case the exhaust gases are sent to a small tunnel where the dilution with air occurs.

As it will be later explained, the mini tunnel allows to stabilize and keep constant the gases flow rate and dilute them to avoid PM composition variations.

While with CVS, real-time monitoring of exhaust gas flow rate is not necessary since the probes sample gases after dilution (sampling a consistent quantity each time), in this system, real-time knowledge of exhaust gas flow rate is crucial as these gases remain undiluted.

Because of the exhaust pulsations, the value of exhaust gases flow rate is very difficult to measure using a flow rate meter. To solve the problem, this value is obtained through the direct measurement of fuel mass flow rates and of the laminar air flow, as follows:

$$\dot{m}_{exh} = \dot{m}_{fuel} + \dot{m}_{air,wet}$$

This equation considers the operating conditions during which the fuel injection goes to zero, thus allowing to always have a value different from zero. Air and fuel measurement have been already described in this chapter. It is worth noting that this measurement is very precise, thanks to the high exhaust gas sampling frequency of about 50 Hz.

In the following figure a very general layout of exhaust gas sampling system and the analyzers is depicted:

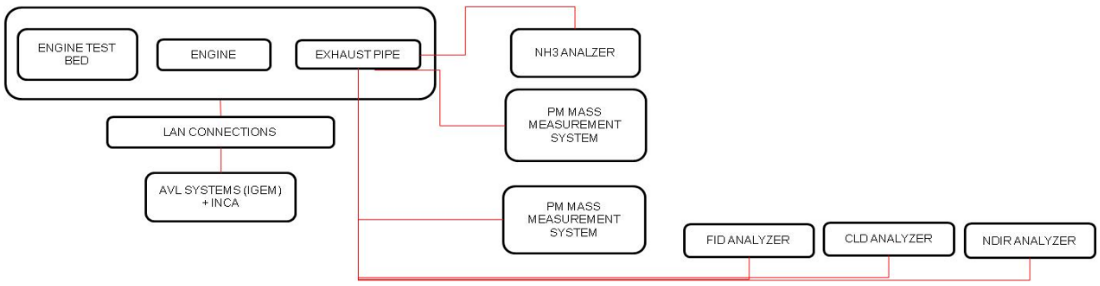

FIGURE 4.14 - EXHAUST GAS SAMPLING SYSTEM LAYOUT

4.3.1 Gaseous pollutants measurement

Commonly employed techniques for analyzing exhaust gas constituents rely on specific physical properties of the gas being measured. Even when the measured species undergoes a chemical reaction within the analyzer, only an associated physical property is directly assessed. Gas concentrations are determined by comparing the instrument signal to that produced by a calibration gas with precisely known concentrations.

Technique	**Gas**	**Typical Range**	**Response Time (t90)**
Non-dispersive infra-red (NDIR)	CO	0-3000 ppm	2-5 s
	CO_2	0-20%	2-5 s
Chemiluminescence (CLD)	NO_X	0-10000 ppm	1.5-2 s
Flame ionization detector (FID)	HC	0-10000 ppm	1-2 s
Fast FID	HC	0-2000 ppm	1-2 ms
Fourier Transform infra-red (FTIR)	NO_x	Various	5-15 s

TABLE 4.1 - POLLUTANT MEASUREMENT TECHNIQUES OVERVIEW

"Response time" means the difference in time between a rapid change of the component to be measured at the reference point and the appropriate change in the response of the measuring system whereby the change of the measured component is at least 60 per cent Full Scale (FS) and takes place in less than 0.1 second. The system response time (t90) consists of the delay time to the system and of the rise time of the system.

"Rise time" means the time between the 10 per cent and 90 per cent response of the final reading (t90 – t10). This is the instrument response after the component to be measured has reached the instrument. For the rise time, the sampling probe is defined as the reference point [31].

- The NDIR technique

As already specified, NDIR stands for Non-Dispersive Infra-Red. It is a technique implied in the instrumentation of a test bench cell for measuring the concentration of carbon monoxide (CO) and carbon dioxide (CO_2) contained in the exhaust gases. In the next picture, a general scheme of the measurement instrumentation is shown:

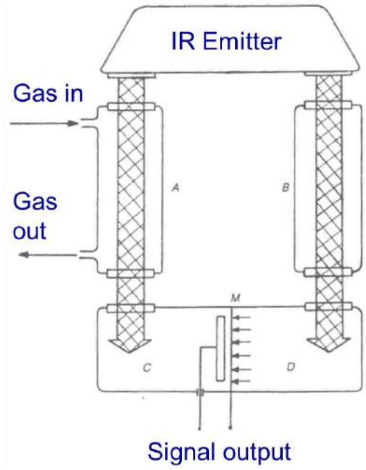

FIGURE 4.15 - NDIR TECHNIQUE *

NDIR technique exploit a particular property of certain gases that, when exposed to infrared rays, absorb a portion of them while the others are reflected. The capability to absorb a certain range of rays' wavelength depends on the atomic structure of the observed gas. This range is about 0.75 – 30 µm, so near and middle infrared. Molecules composed of atoms from at least two different elements (such as CO, NO, NO2, SO2, etc.) absorb infrared radiation by converting light energy into vibrational and rotational energy, which can then be detected as heat.

Referring to the previous picture, an infrared rays emitter sends its radiation to the measurement cells C and D, which contain gas identical to that to be analyzed (e.g. CO_2). Between these cells there is a membrane, which is basically a differential sensor (M) consisting of a diaphragm that moves between plates of a capacitor. Between the IR emitter and the cells C and D, there are other two cylinders (A and B) that have the bottom which is transparent to infrared rays. In cylinder B (which is also called reference cell) there can be either nitrogen or pure air, while in cylinder A there is the gas to be measured (in concentration). The difference in heat received in each chamber due to the presence of the analyzed gas on the path of one of the half-beams causes increased pressure on one side of the diaphragm. So, if the input gas in cell A is the same gas of cell B, the energy in cells C and D is the same and the detector doesn't notice anything (on the membrane it is applied the same force from both the sides). On the contrary, when in cell A there is

CO, it absorbs part of the infrared rays proportionally to its concentration. So cell C notices an amount of energy that is lower than the cell D and the membrane moves from cell D to cell C. Its movement is converted in an electric signal, proportional to the concentration of the gas to be detected.

The pressure is modulated by the rotating chopper turning at a frequency of about 10 Hz. The output signal from the cell represents the variations of capacitance of the system. The relationship between the signal output and the gas concentration is not linear, thus requiring several calibration points. The adsorbed energy (E_a) from the gases in the cells is a fraction of the total incident energy (E_i). Their bond is expressed with the following equation:

$$E_a = E_i \cdot (1 - e^{-kcL})$$

Where:

- k is the adsorption coefficient of the gas;
- c is the concentration of the species of interest;
- L is the length of the cell.

If the product kcL is a lot lower than the unit, the adsorbed energy may be considered directly proportional to the concentration c:

$$kcL \ll 1 \rightarrow \; E_a = E_i \cdot (1 - e^{-kcL}) \sim E_i kcL$$

This instrument cannot operate on wet gases, since H_2O vapor may interfere with CO and CO_2 absorption wavelengths. Analysis must therefore be done only on dry gases, condensing the vapor in a cooling system, and then heating the sample to ambient temperature before going to the analyzer [31].

- FID Analyzer

FID stands for "flame ionization detector" and it is a measurement technique used to determine the concentration of hydrocarbons (HC) in the exhaust gases. The operating principle is based on the production of free electrons and positive ions during the combustion of hydrocarbons in a flame of hydrogen that is non-ionized. The scheme is presented below:

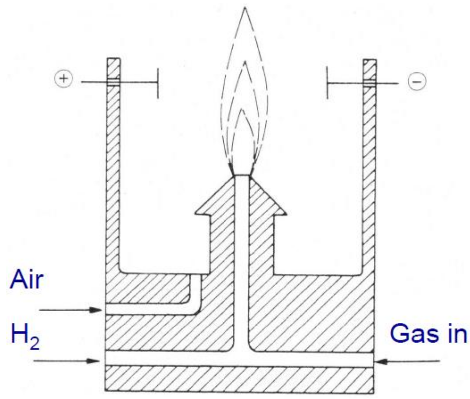

FIGURE 4.16 - FID ANALYZER*

The gas to be analyzed is sent to a burner, where there is the flame produced by a mixture of 40% of hydrogen and 60% of helium, mixed in turn with air. On the top of the flame there are two electrodes, where a voltage drop (between 100 and 300 V) is kept. If the gas contains a certain amount of carbon atoms, it produces an high ionization, that is proportional to the amount of burned carbon. Since the ions are electrically charged, in case of presence of HC in the gas, a current between the two electrodes is generated.

If all the electrical charges are collected on the electrodes, for each hydrocarbon (C_nH_m) the measured current is:

$$I = r \cdot [C_nH_m] \cdot Q$$

Where:

- Q is the volume flow rate of the gas sample through the sensor;
- C_nH_m is the molar concentration of the hydrocarbon;
- r = αn is the response of the FID.

The instrument gives a signal proportional to the amount of carbon in the analyzed gas. Some disturbances to the measurement can be provoked by an high speed of the fuel jet, that may push the charges out of the electrical field between the electrodes. Still, an high density of the charge could prevent the penetration of the electrical field between the electrodes [31].

- CLD analyzer

The chemiluminescence detector (CLD) technique is primarily used for measuring nitrogen oxides (NO_x), specifically nitric oxide (NO) and nitric dioxide (NO_2) that are present in the exhaust gases. In the CLD method, nitric oxide reacts with ozone (O_3) to produce excited nitrogen dioxide (NO_2*), which emits light (chemiluminescence) when it returns to its ground state. The reactions are the following:

$$NO + O_3 \rightarrow NO_2^* + O_2$$

$$NO_2^* \rightarrow NO_2 + h\nu$$

Ozone is produced in the instrument by an high-voltage discharge in oxygen. When the nitrogen dioxide molecules are excited, they spontaneously returns to the normal state. During this transition, red light with photons in the 0.6 ÷ 3 μm band are emitted. The light emission is then captured by a photo multiplier and transformed into an electrical signal. This signal is proportional to the NO concentration in the sample, as shown in this equation:

$$I \propto \frac{[NO][O_3]}{M}$$

The scheme of the measurement system is here depicted:

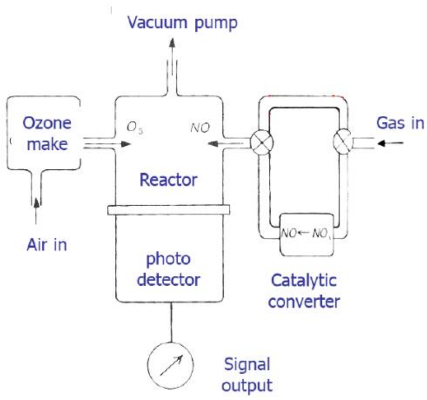

FIGURE 4.17 - CHEMILUMINESCENCE DETECTOR*

In the reactor of the analyzer there is a vacuum pump that checks the pressure in the chamber and inlets the ozone and sample gas inside. The ozone is generated either through an electric discharge or by UV rays at low pressure.

The volume flow rate of the ozone is determined by the supply pressure of the oxygen and a capillary near the ozonator. The sample gas flow rate is regulated by two capillaries. A sampling pump sends the flow in excess to the reactor; the excess constitutes the bypass flow and is regulated by a capillary. This ensure that the ozone flow is constant.

One of the goals of the instrumentation is to measure the NO2 concentration, therefore the gas is forced through a catalytic converter. Here, thanks to the presence of an electric resistance, NO_2 is transformed into NO:

$$NO_2 \leftrightarrow NO + O$$

The gas to be analyzed is sent through a stainless-steel pipe, heated to 600-700°C by an electric resistance. At this temperature, the NO remains unaffected, while the NO_2 is transformed into NO. Consequently, the instrument measures the total amount of NOx (NO + NO2) in the exhaust gases, quantified as NO [31].

* The pictures are taken from the PowerPoint slides of the course of Engine Emission Control of Professor Federico Millo, Politecnico di Torino.

- Particulate matter measurement

Diesel particulate matter (PM) is a complex mixture with varying chemical and physical properties, influenced by fuel type, engine technology, operating conditions, and exhaust after treatment. Its characteristics change over time due to processes like coagulation and evaporation, both in the atmosphere and within sampling equipment, potentially creating artifacts that don't exist in real-world conditions. Unlike gaseous emissions, there is no single absolute measure for diesel PM emissions because the definition and measurement of diesel PM depend on the specific technique used, making all measures somewhat arbitrary.

The measurements performed in the test bench facilities dedicated to the engine homologation are three:

- Particle mass;
- Particle number;
- Smoke opacity.

Particle mass

Regulatory and compliance testing requires gravimetric diesel PM determination in conjunction with the constant volume sampling (CVS) technique. The exhaust gases from the engine are mixed with an amount of air in the so-called dilution tunnel. A sample of gas from the dilution tunnel is drawn through fiberglass filters. The filters are than weighed on a very high precision balance placed in a controlled temperature ambient, with controlled relative humidity.

The filter is weighted before and after the measurement. Prior to the test, the filter is conditioned for a minimum of 48 hours. After the test, the filter must be conditioned for at least 1 hour before weighing. The PM mass is determined by the difference in the filter's mass before and after the test cycle.

The PM mass measurement is quite challenging because the particulate is very unstable. Indeed, if subjected to sudden changes in the environmental conditions, PM changes its composition, favoring the condensation of other substances. The dilution with air affects the soluble fraction of the PM, but it is irrelevant on the PM solid fraction. The Dilution rate may avoid the condensation of the HC on the PM particles.

PM number

The number of particulate matter (PM) is measured using a condensation particle counter (CPC). Inside the CPC, the aerosol stream is saturated with alcohol vapor, typically butanol. When the mixture is cooled in the condenser tube, the vapor condenses on the particles, causing them to grow to about 10 μm, which allows for optical detection. The detection limit for particle size in the CPC depends on the saturation ratio, which increases as particle diameter decreases. Modern CPCs can detect particles as small as 10 nm, and some can detect ultrafine particles as small as 3 nm.

CPCs can operate in two modes: counting mode and total intensity mode. In counting mode, scattered light pulses from individual particles are counted, providing the most accurate measurements but only suitable for low particle concentrations. In total intensity mode, used for concentrations typically above 10^4 particles per cubic centimeter, the number is determined from the total light scattering intensity. This mode is generally less accurate and requires that all particles grow to the same diameter and frequent calibration of the optical system.

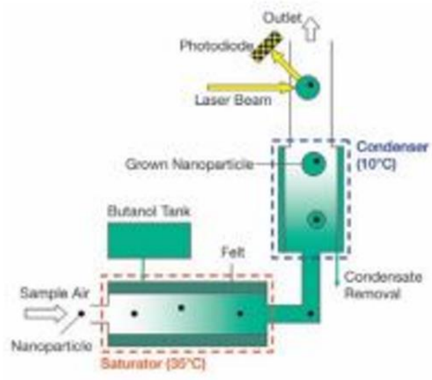

FIGURE 4.18 - PM NUMBER COUNTER SCHEME

Smoke opacity

Opacity (OPA) is defined as the percentage of incident light intensity (I_0) that is not transmitted by exhaust gases. An opacimeter measures this quantity by using a light source and a photocell aligned on the same axis. When exhaust gas fills the space in between, the signal received by the photocell decreases. This decrement is greater when there are more solid particles in the gas, as the latter absorb the light, preventing it from reaching the photocell. If I (power/surface) is the light intensity at the photo-receiver, opacity (OPA) is defined as:

$$OPA = \left(1 - \frac{I}{I_0}\right) \cdot 100 = (1 - N) \cdot 100$$

Where:

- $I = I_0 \cdot e^{-naQl}$
- n is the volume concentration of particles;
- a depends on the physical characteristics of adsorbing;
- Q depends on the dimensions and from the form of the particles.

5. Homologation dyno tests

This chapter is dedicated to the description of the tests performed on the engine test bench. The focus will be on the tests prescribed by the testing requirements for type approval, that are established in the Euro VI step E emission regulation. As already mentioned in the chapter first, the tests are the transient test cycle (WHTC), the ramped steady state test cycle (WHSC) and the emission off-cycle test (WNTE).

5.1 World harmonized transient cycle (WHTC)

WHTC is a test cycle, which consists of a sequence of test points each with a defined speed and torque to be followed by the engine under transient operating conditions.

The test has been proposed by the global technical regulation (GTR) developed by the UN ECE GRPE group. The GTR covers a world-wide harmonized heavy-duty certification (WHDC) procedure for engine exhaust emissions. This test procedures reflect worldwide on-road heavy-duty engine operation, as closely as possible, and provide a marked improvement in the realism of the test procedure for measuring the emission performance of existing and future heavy-duty engines [32].

More basically, the transient test cycle is a second-by-second sequence of normalized speed and torque values. Normalized means that both speed and torque values are expressed in percentage. The regulation gives speed and torque profile in percentage because in this way it is ensured that each engine, even of different technical specifications, is subjected to the same test.

To perform the test in the engine test cell, the normalized values shall be converted to the actual values for the individual engine under test, based on the engine-mapping curve. The curves obtained after denormalization are no longer expressed in percentage but in Nm, rpm, and kW respectively for torque, engine speed and power profiles. The conversion is referred as denormalization, and the new test cycle so developed becomes the “reference cycle” of the engine to be tested.

For validating the test cycle, the actual speed, torque, and power values obtained during the test shall be recorded. After the test, a regression analysis is conducted by comparing the actual values to the reference values. This analysis will verify the accuracy of the test run.

For calculation of the brake specific emissions, the actual cycle work shall be calculated by integrating actual engine power over the cycle. For cycle validation, the actual cycle work must be within prescribed limits of the cycle work of the reference cycle [34].

The gaseous pollutants may be recorded continuously or sampled into a sampling bag. The particulate sample shall be diluted with conditioned ambient air and collected on a single suitable filter.

The WHTC cycle is schematically shown hereafter:

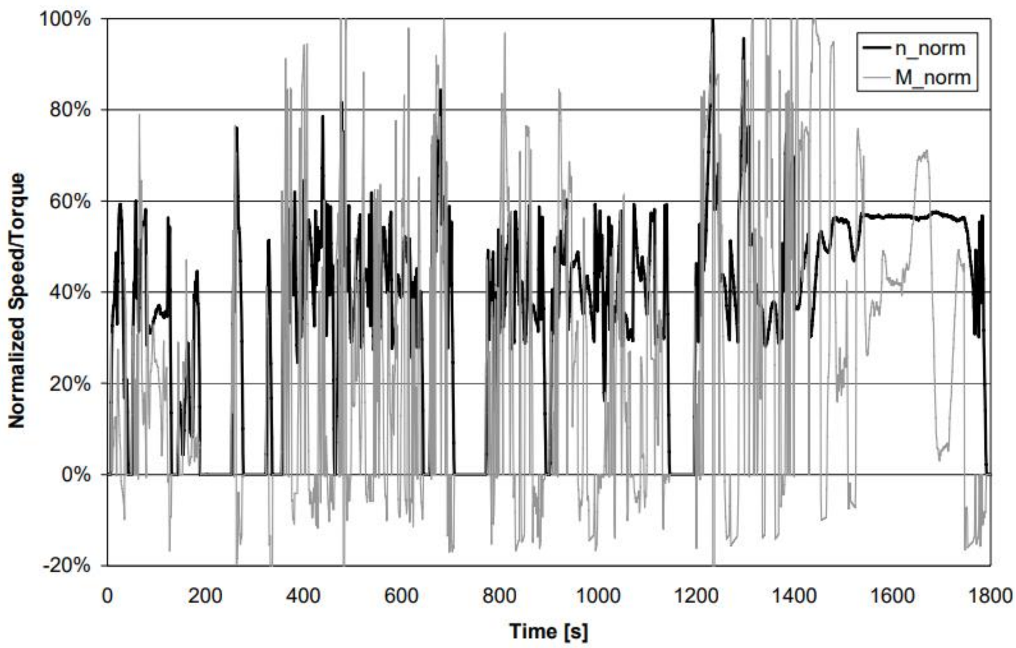

FIGURE 5.1 - WHTC TEST CYCLE

5.2 Ramped steady state test cycle (WHSC)

The ramped steady state test cycle (WHSC) involves several normalized speed and load modes covering the typical operating range of heavy-duty engines. The engine is operated for a set time in each mode, with speed and load changing linearly within 20 seconds. During each mode and the transitions between them, the concentration of gaseous pollutants, exhaust flow, and power output are measured and averaged over the cycle. Gaseous pollutants can be recorded continuously or sampled into a bag, and particulate samples are diluted with conditioned ambient air, and collected on a single filter. The WHSC is shown in the following table [34]:

Mode	Normalized speed (%)	Norm. load (%)	Mode length (s) + 20s ramp
0	Motoring	-	-
1	0	0	210
2	55	100	50
3	55	25	250
4	55	70	75
5	35	100	50
6	25	25	200
7	45	70	75
8	45	25	150
9	55	50	125
10	75	100	50
11	35	50	200
12	35	25	250
13	0	0	210

TABLE 5.1 - WHSC MODES

5.3 General test sequence

The following flow chart outlines the general guidance that must be followed during the testing.

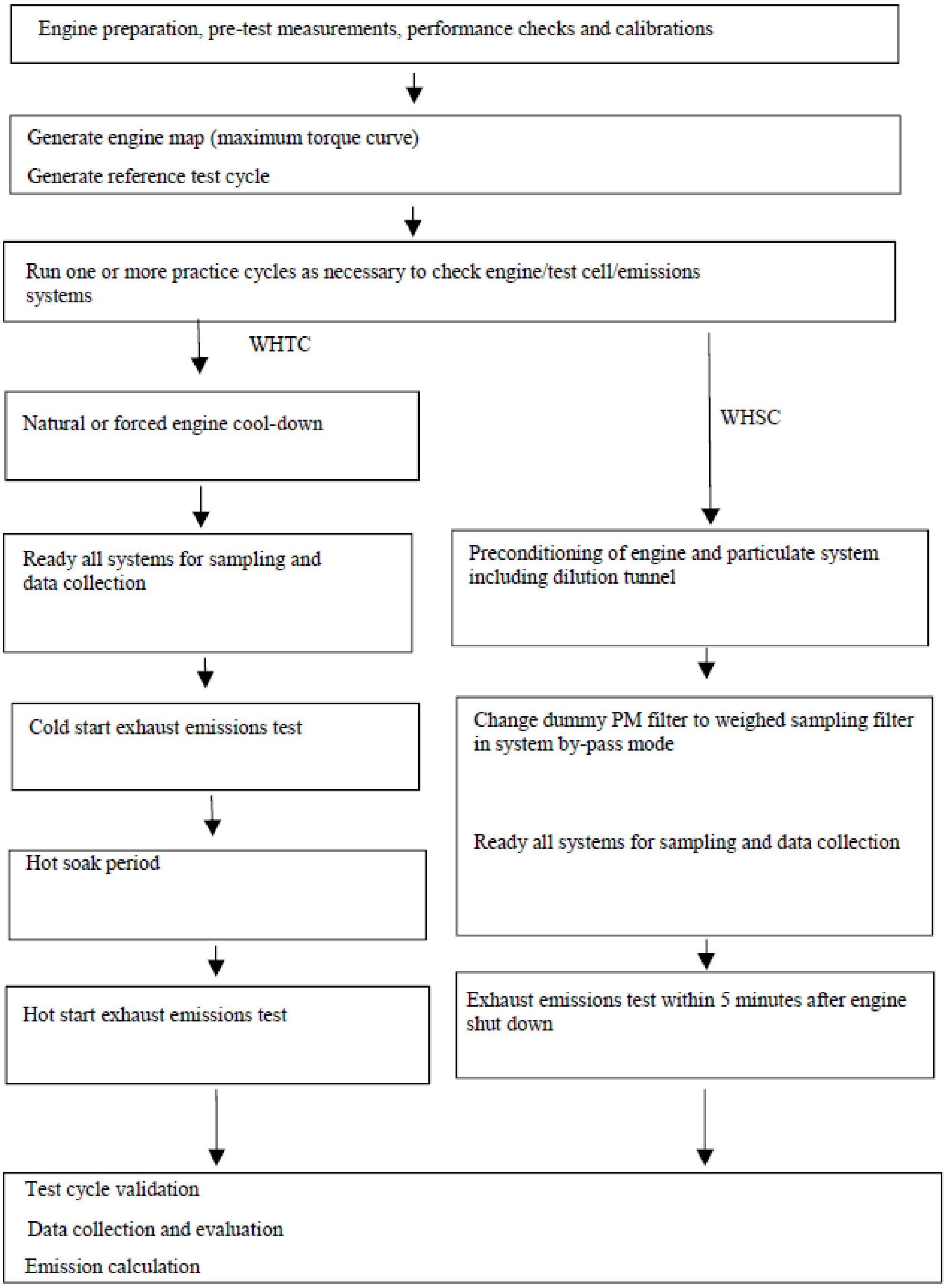

FIGURE 5.2 - TEST SEQUENCE*

The rules presented in the chart are mandatory but variations, where appropriate, are allowed. In this paragraph, some passages of the test sequence are better clarified.

* Picture is taken from the European regulation (EC) No 595/2009 of the European Parliament and of the Council of 18 June 2009

Engine mapping procedure

This represents a fundamental passage for executing the homologation cycles. Before performing the WHTC and WHSC cycles on the test cell, the engine shall be mapped for determining the speed versus torque and speed versus power curves. The engine mapping curve, indeed, makes it possible to do the denormalization of the cycles, to obtain the reference ones.

From a practical point of view, the first action to do is the stabilization of the engine parameters. For doing so, the engine should be warmed up at maximum power according to the manufacturer's recommendations and best engineering practices. In particular, the engine should be operated for at least 2 minutes, to let the oil and cooling water temperature reach a value that falls within 2% of their average operating values. The range of mapping goes from the idle speed to the maximum mapping speed, which is determined as the smallest value between $n_{hi} \cdot 1{,}02$ and the speed where full load torque drops to zero. Once stabilized, to map the engine the steps are:

- Run the engine at idle speed with no load.
- Set the injection pump to full load and operate the engine at the minimum mapping speed.
- Increase the engine speed at an average rate of 8 ± 1 min^{-1}/s from minimum to maximum mapping speed. Record the engine speed and torque points at least once per second [34].

An engine does not need to be mapped before each test cycle. It shall be remapped only in case:

- an unreasonable amount of time has passed since the last map;

- physical changes or recalibrations have been made to the engine, which could affect engine performance [34].

Generation of the reference test cycles

The first step to obtain the reference cycles is the speed denormalization. The speed is denormalized through the following equation:

$$n_{ref} = n_{norm} \cdot (0{,}45 \cdot n_{lo} + 0{,}45 \cdot n_{pref} + 0{,}1 \cdot n_{hi} - n_{idle}) \cdot 2{,}0327 + n_{idle}$$

The terms of the equation are hereafter explained:

- n_{norm} is the normalized speed shown in the figure 5.1 and table 5.1;
- n_{lo} is the lowest speed where the power is 55 % of maximum power;
- n_{hi} is the highest speed where the power is 70 % of maximum power;
- n_{idle} is the idle speed;
- n_{95h} is the speed corresponding to the 95 % of maximum power.

In the following picture the definition of test speeds is shown [34].

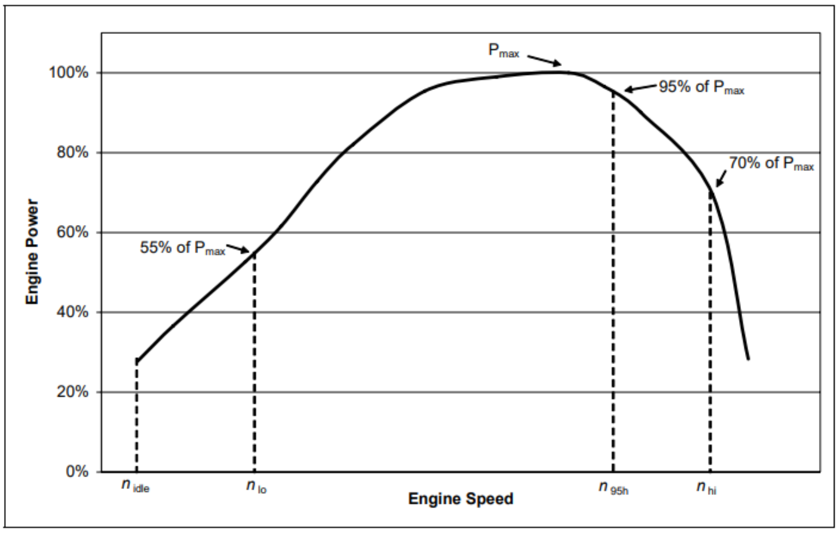

FIGURE 5.3 - DEFINITION OF TEST SPEEDS*

The next step is the determination of the preferred speed (n_{pref}) defined as the engine speed where the maximum torque integral is 51 % of the whole integral (between n_{idle} and n_{95h}). As shown in the following figure:

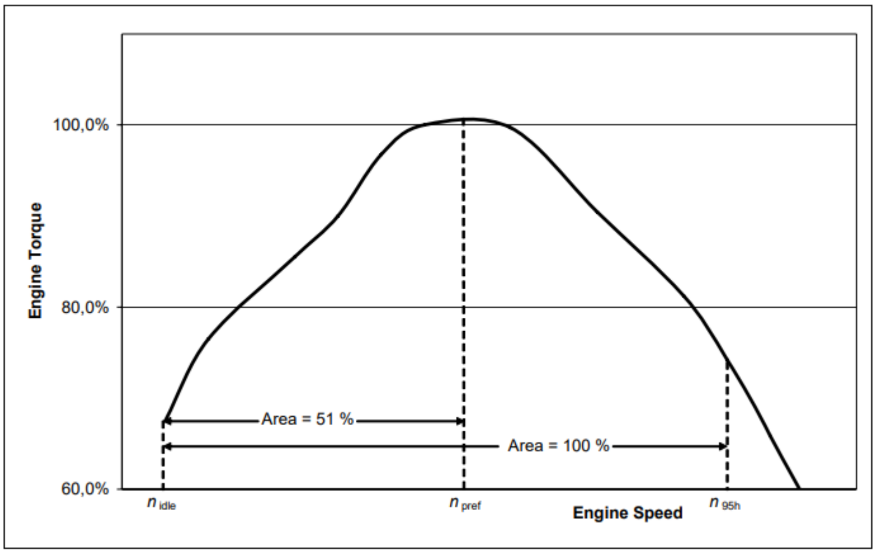

FIGURE 5.4 - DEFINITION OF PREFERRED SPEED*

After the speed denormalization another quantity that has to be denormalized is the torque. In order to obtain the reference cycles, the torque must be denormalized using the curve previously obtained. The reference torque is computed through the following equation:

$$M_{ref,i} = (M_{norm,i}/100) \cdot M_{max,i} + M_{f,i} - M_{r,i}$$

Where:

- $M_{norm,i}$ is the normalized torque, expressed in percentage;
- $M_{max,i}$ is the maximum torque of the mapping curve in Nm;
- $M_{f,i}$ is the torque adsorbed by auxiliary devices and equipment installed in Nm;
- $M_{r,i}$ is the torque adsorbed by auxiliary devices or by equipment to be removed in Nm.

Finally, the reference work produced during the cycle is computed. This is done by calculating the instantaneous values of the power at the engine reference speed and reference torque simultaneously. These values are integrated over the cycle to determine the reference work produced during the test cycle, which is expressed in kWh. The same method is used to determine both the reference power and the effective power. For integrating the work produced during the effective cycle, all negative torque values are computed and set to zero [34].

* Pictures taken from the European regulation (EC) No 595/2009 of the European Parliament and of the Council of 18 June 2009

Pre-test operations

Before the execution of the homologation cycles, some preliminary operations are requested. The regulation, indeed, says that engine measurements, performance checks and system calibration should be made prior to the engine mapping procedure. In the following list these actions are better clarified [34].

1. **Preparation of measurement equipment for sampling**
   Before collecting emission samples, a leak check must be performed within the preceding 8 hours. Measurement instruments should be started according to the manufacturer's guidelines and sound engineering practices. All dilution systems, sample pumps, cooling fans, and the data-collection system need to be activated. Heat exchangers in the sampling system should be preheated or precooled to their operating temperature range. Adjust flow rates to the desired levels using bypass flow. Ensure that heated or cooled components are stabilized at their operating temperatures. The exhaust dilution system should be switched on at least 10 minutes before starting the test sequence. Finally, reset all electronic integrating devices before initiating any test interval [34].

2. **Preparation of the particulate sampling filter**
   At least one hour before the test, the filter shall be placed in a petri dish, which is protected against dust contamination and allows air exchange and placed in a weighing chamber for stabilization. At the end of the stabilization, the filter shall

be weighted, and the tare weight recorded. The filter shall then be stored in a closed petri dish or sealed until needed for testing. The filter shall be used within eight hours of its removal from the weighing chamber [34].

3. **Installation of the measuring equipment**
   The instrumentation and sample probes shall be installed as required. The exhaust pipe shall be connected to the full flow dilution system.

4. **Adjustment of the dilution system**
   The total diluted exhaust gas flow of a full flow dilution system or the diluted exhaust gas flow through a partial flow dilution system shall be set to eliminate water condensation, and to obtain a filter face temperature between 42°C and 52°C.

WHTC cycle run

The World Harmonized Test Cycle (WHTC) consists of three phases: a cold start test, a hot soak period, and a hot start test.

The cold start test begins when the temperatures of the engine's lubricant, coolant, and after-treatment systems are all between 20°C and 30°C. This requires natural or forced cooling of the engine, which involves inducing cold air through the intake, circulating cool oil through the engine oil circuit, dissipating heat from the coolant via the engine cooling system, and removing heat from the exhaust gases and after-treatment systems [34].

Once cooled, the engine is started using one of the following methods:

- starting the engine as recommended in the owner's manual with a production starter motor and a fully charged battery or suitable power supply;
- using the dynamometer to motor the engine within ±25% of its typical in-use cranking speed, stopping cranking within 1 second after the engine starts running.

Immediately following the cold start test, the engine undergoes a hot soak period of 10 ± 1 minutes to condition it for the hot start test.

The hot start test begins at the end of the hot soak period using the same starting procedures as the cold start test. Both cold and hot start test sequences commence at engine start. Once the engine is running, cycle control initiates to match the engine operation with the first set point of the cycle, following the reference WHTC cycle. Engine speed and torque command set points are issued at 5 Hz (10 Hz recommended) or higher, computed by linear interpolation between the 1 Hz set points of the reference cycle. Torque and engine speed are recorded at least every second (1 Hz) during the test, with signals electronically filtered [34].

Simultaneously with the test sequence start, measuring equipment begins collecting emission data:

- if using a full flow dilution system, start collecting and analyzing diluent;
- collect or analyze raw or diluted exhaust gas, depending on the chosen method;
- measure and record the amount of diluted exhaust gas and required temperatures and pressures;
- record the exhaust gas mass flow rate if analyzing raw exhaust gas;
- record feedback data of speed and torque from the dynamometer.

For raw exhaust measurements, emission concentrations (NMHC, CO, and NOx) and the exhaust gas mass flow rate are continuously measured and stored at least 2 Hz on a computer system. Other data can be recorded at a sample rate of at least 1 Hz. For analog analyzers, the response is recorded, and calibration data can be applied online or offline during data evaluation.

If using a full flow dilution system, HC and NOx are measured continuously in the dilution tunnel with at least 2 Hz frequency, and average concentrations are determined by integrating the analyzer signals over the test cycle. The system response time must not exceed 20 seconds and should be coordinated with CVS flow fluctuations and sampling time/test cycle offsets if necessary. CO, CO2, and NMHC can be determined by integrating continuous measurement signals or analyzing concentrations in the sample bag collected over the cycle. Gaseous pollutant concentrations in the diluent are determined before the exhaust enters the dilution tunnel by integration or collecting into a background bag. All other parameters are recorded with a minimum of one measurement per second (1 Hz) [34].

WHSC cycle run

The initial step in the WHSC test cycle involves starting and warming up the engine and dilution system, following the same procedures used in the WHTC cycle. Once warmed up, the engine and sampling system should be preconditioned by running the engine at mode 9 from table 5.1 for at least 10 minutes. After preconditioning, the engine must be turned off and left for a minimum of 5 minutes. Subsequently, the engine should be restarted using the previously described procedures. The WHSC test cycle can then commence, adhering to the methods and timings outlined in table 5.1. The requirements for emission data collection and particulate sampling are identical to those in the WHTC test cycle. [34].

Post test procedures

At the completion of the test, the measurement of the exhaust gas mass flow rate, the diluted exhaust gas volume, the gas flow into the collecting bags and the particulate sample pump shall be stopped. For an integrating analyzer system, sampling shall continue until system response times have elapsed.

For any proportional batch sample, such as a bag sample or PM sample, it shall be verified that proportional sampling was maintained. Any sample that does not fulfil the requirements shall be voided.

The particulate filter shall be placed into covered or sealed containers, or the filter holders shall be closed, in order to protect the sample filters against ambient contamination. They shall be returned to the weighing chamber. The filter shall be conditioned for at least one hour, then weighed and recorded [34].

Drift verification

As soon as practical but no later than 30 minutes after the test cycle is complete or during the soak period, the zero and span responses of the gaseous analyzer ranges used shall be determined. The test cycle is defined as follows:

- For the WHTC: the complete sequence cold – soak – hot;
- For the WHTC hot test: the sequence soak – hot;
- For the multiple regeneration WHTC hot start test the total number of hot start test;
- For the WHSC: the test cycle.

The following provisions apply for analyser test:

- If the drift difference between the pre-test and the post-test results is equal to or greater than 1% of full scale, the measured concentrations may be used uncorrected or the measured concentrations shall be corrected for drift;
- If the drift difference between the pre-test and the post-test results is equal or greater than 1%, the test shall be voided, or the measured concentrations shall be corrected for drift.

The bag samples must be analysed within 30 minutes after the hot start test is complete or during the soak for the cold start test. The bottom samples must be analysed within 60 minutes after the hot start test is complete.

For the calculation of the produced work over the effective cycle, the points recorded during the engine starting can be omitted. To calculate the instantaneous engine power, effective speed and torque values are used simultaneously. Then the effective work W_{act} (kWh) is obtained through the integration of the instantaneous power over the complete cycle.

The effective work is necessary for a comparing with the reference cycle work W_{ref} and for the bench specific emissions calculation. The value of W_{act} must be included between the 85 and 105 % of the W_{ref} [34].

Validation statistics of the test cycle

As previously anticipated, a linear regression of the actual values ($\eta_{act}, M_{act}, P_{act}$) on the reference values ($\eta_{ref}, M_{ref}, P_{ref}$) shall be performed for both WHTC and WHSC test cycles.

To minimize the biasing effect caused by the time lag between the actual and reference cycle values, the entire sequence of actual engine speed and torque signals can be adjusted in time relative to the reference speed and torque sequence. If adjustments are made, both speed and torque signals must be shifted by the same amount and in the same direction.

The method of least squares shall be used, with the best-fit equation having the following form:

$$y = a_1 x + a_0$$

Where:

- y is the actual value of speed (min^{-1}), torque (Nm), or power (kW);
- a_1 is the slope of the regression line;
- x is the reference value of speed (min^{-1}), torque (Nm), or power (kW);
- a_0 is the y intercept of the regression line.

The Standard Error of Estimate (SEE) of y on x and the coefficient of determination (r^2) shall be calculated for each regression line.

It is recommended that this analysis be performed at 1 Hz. For a test to be considered valid, the criteria of WHTC and WSCH shall be met. They are shown in the following figures.

	Speed	*Torque*	*Power*
Standard Error of Estimate (SEE) of y on x	maximum 5 per cent of maximum test speed	maximum 10 per cent of maximum engine torque	maximum 10 per cent of maximum engine power
Slope of the regression line, a_1	0.95 to 1.03	0.83 - 1.03	0.89 - 1.03
Coefficient of determination, r^2	minimum 0.970	minimum 0.850	minimum 0.910
y intercept of the regression line, a_0	maximum 10 per cent of idle speed	±20 Nm or ±2 per cent of maximum torque whichever is greater	±4 kW or ±2 per cent of maximum power whichever is greater

FIGURE 5.5 - REGRESSION LINE TOLERANCES FOR WHTC*

	Speed	*Torque*	*Power*
Standard Error of Estimate (SEE) of y on x	maximum 1 per cent of maximum test speed	maximum 2 per cent of maximum engine torque	maximum 2 per cent of maximum engine power
Slope of the regression line, a_1	0.99 to 1.01	0.98 - 1.02	0.98 - 1.02
Coefficient of determination, r^2	minimum 0.990	minimum 0.950	minimum 0.950
y intercept of the regression line, a_0	maximum 1 per cent of maximum test speed	±20 Nm or ±2 per cent of maximum torque whichever is greater	±4 kW or ±2 per cent of maximum power whichever is greater

FIGURE 5.6 - REGRESSION LINE TOLERANCES FOR WHSC*

For regression purposes only, point omissions are permitted where noted in the next figure. Before doing the regression calculation. However, those points shall not be omitted for the calculation of cycle work and emissions. Point omission may be applied to the whole or to any part of the cycle [34].

Event	*Conditions*	*Permitted point omissions*
Minimum operator demand (idle point)	n_{ref} = 0 per cent and M_{ref} = 0 per cent and $M_{act} > (M_{ref} - 0.02\ M_{max.\ mapped\ torque})$ and $M_{act} < (M_{ref} + 0.02\ M_{max.\ mapped\ torque})$	speed and power
Minimum operator demand (motoring point)	M_{ref} < 0 per cent	power and torque
Minimum operator demand	$n_{act} \leq 1.02\ n_{ref}$ and $M_{act} > M_{ref}$ or $n_{act} > n_{ref}$ and $M_{act} \leq M_{ref}$ or $n_{act} > 1.02\ n_{ref}$ and $M_{ref} < M_{act} \leq (M_{ref} + 0.02\ M_{max.\ mapped\ torque})$	power and either torque or speed
Maximum operator demand	$n_{act} < n_{ref}$ and $M_{act} \geq M_{ref}$ or $n_{act} \geq 0.98\ n_{ref}$ and $M_{act} < M_{ref}$ or $n_{act} < 0.98\ n_{ref}$ and $M_{ref} > M_{act} \geq (M_{ref} - 0.02\ M_{max.\ mapped\ torque})$	power and either torque or speed

FIGURE 5.7 - PERMITTED POINT OMISSIONS FROM REGRESSION ANALYSIS*

* Picture are taken from the European regulation (EC) No 595/2009 of the European Parliament and of the Council of 18 June 2009

5.4 Off-cycle emission (OCE)

Euro VI regulation has introduced off-cycle emission (OCE) testing requirements. OCE measurements, that are performed during type-approval testing, have two pieces:

- laboratory testing following NTE (Not-To-Exceed) limit approach;
- in-use PEMS testing.

The PEMS procedure at type approval is like PEMS testing for In-Service Conformity (ISC), that will be treated later in this thesis. In this chapter the focus will be on World-harmonized Not-To-Exceed (WNTE) emission requirements, based on laboratory testing. The WNTE is basically a test cycle performed on the bench, that allows to determine gaseous and particulate exhaust emissions, specifically NO_x, *CO, HC, and PM.* Exhaust emissions shall not exceed the applicable WNTE emission limits reported below [34].

The applicable WNTE emission limits are determined, as follows:

$$WNTE\ Emission\ Limit = WHTC\ Emission\ Limit + WNTE\ Component$$

Where:

- "WHTC Emission Limit" is the emission limit (EL) to which the engine is certified pursuant to the WHDC gtr;
- "WNTE Component" is determined by the following equations.

The applicable WNTE components shall be determined using the following equations, when the ELs are expressed in g/kWh:

$$For\ NO_x:\quad WNTE\ Component = 0{,}25\ \cdot EL + 0{,}1\ [\frac{g}{kWh}]$$

$$For\ HC:\quad WNTE\ Component = 0{,}15\ \cdot EL + 0{,}07\ [\frac{g}{kWh}]$$

$$For\ CO:\quad WNTE\ Component = 0{,}20\ \cdot EL + 0{,}2\ [\frac{g}{kWh}]$$

$$For\ PM:\quad WNTE\ Component = 0{,}25\ \cdot EL + 0{,}003\ [\frac{g}{kWh}]$$

The WNTE test cycle is performed in a defined control area of the engine. It consists of the engine speeds and load points represented in the following picture and described immediately afterwards [34].

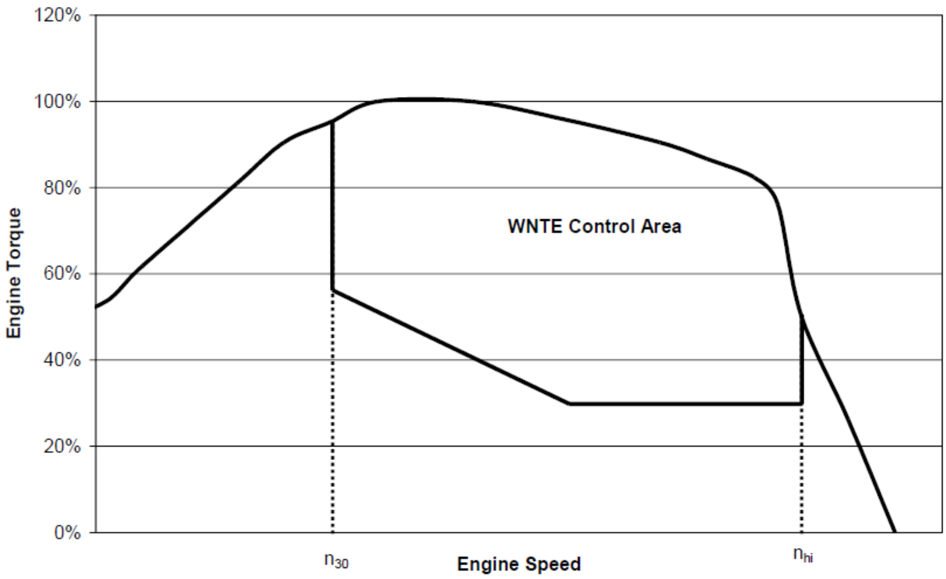

FIGURE 5.8 - WNTE CONTROL AREA OF THE ENGINE*

Engine speed range

The WNTE control area shall include all operating speeds between the 30th percentile cumulative speed distribution over the WHTC test cycle, including idle, (n_{30}) and the highest speed where 70 per cent of the maximum power occurs (n_{hi}) [34].

Engine torque range

The WNTE control area shall include all engine load points with a torque value greater than or equal to 30 per cent of the maximum torque value produced by the engine [34].

Engine power range

Speed and load points below 30 per cent of the maximum power value produced by the engine shall be excluded from the WNTE control area for all emissions [34].

The specific mass emissions of regulated pollutants shall be determined based on randomly defined test points distributed across the WNTE control area. All the test points shall be contained within 3 randomly selected grid cells imposed over the control area, as shown below. The grid shall be comprised of 9 cells for engines with a rated speed less than 3000 min^{-1}. The grid is shown below:

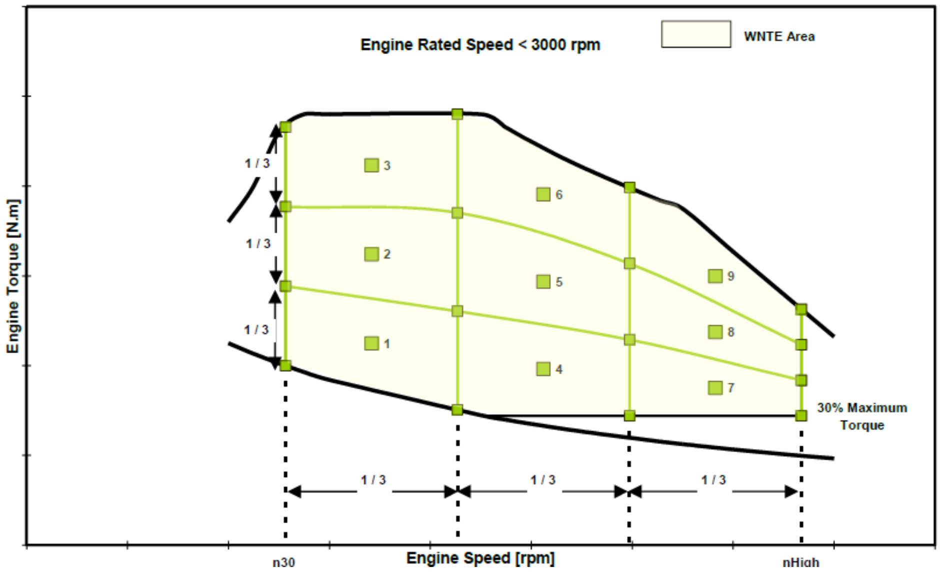

FIGURE 5.9 - WNTE TEST CYCLE GRID*

The 3 selected grid cells shall each include 5 random test points, so a total of 15 random points shall be tested within the WNTE control area. Each cell shall be tested sequentially; therefore all 5 points in one grid cell are tested before transiting to the next grid cell. The test points are combined into a single ramped steady state cycle.

The order in which each of the grid cells are tested, and the order of testing the points within the grid cell, shall be randomly determined. The 3 grid cells to be tested, the 15 test points, the order of testing the grid cells, and the order of the points within a grid cell shall be selected by the Type Approval Authority using acknowledged statistical methods of randomization.

The average specific mass emissions of regulated gaseous pollutants shall not exceed the WNTE limit values, when measured over any of the cycle in a grid cell with 5 test points and over the whole 15 test point cycle [34].

* Picture are taken from the European regulation (EC) No 595/2009 of the European Parliament and of the Council of 18 June 2009

6. Homologation tests results

6.1 The engine power test

The engine power test, as previously anticipated, is the first step to take to execute all the other homologation bench tests. In the table below are reported the main data about the engine under investigation.

ENGINE DATA		
Engine		**********
Serial number		**********
Displacement	[cm^3]	12880
Rated maximum power	[kW]	425
Rated maximum power	[cv]	570,00
Speed at maximum power	[rpm]	1648
Rated maximum torque	[Nm]	2790
Speed at maximum torque	[rpm]	975
Idle speed	[rpm]	548
Maximum speed unload	[rpm]	2051,6
Ambient pressure	[mbar]	1,013
Relative humidity	[%]	21

TABLE 6.1 - ENGINE DATA

The diagram proposed hereafter shows the measured engine net power and torque. During the power test execution, the measured power and torque must not exceed the declared values respectively of 2 and 4 percent. For non-disclosure agreement, the relevant numbers have been obscured.

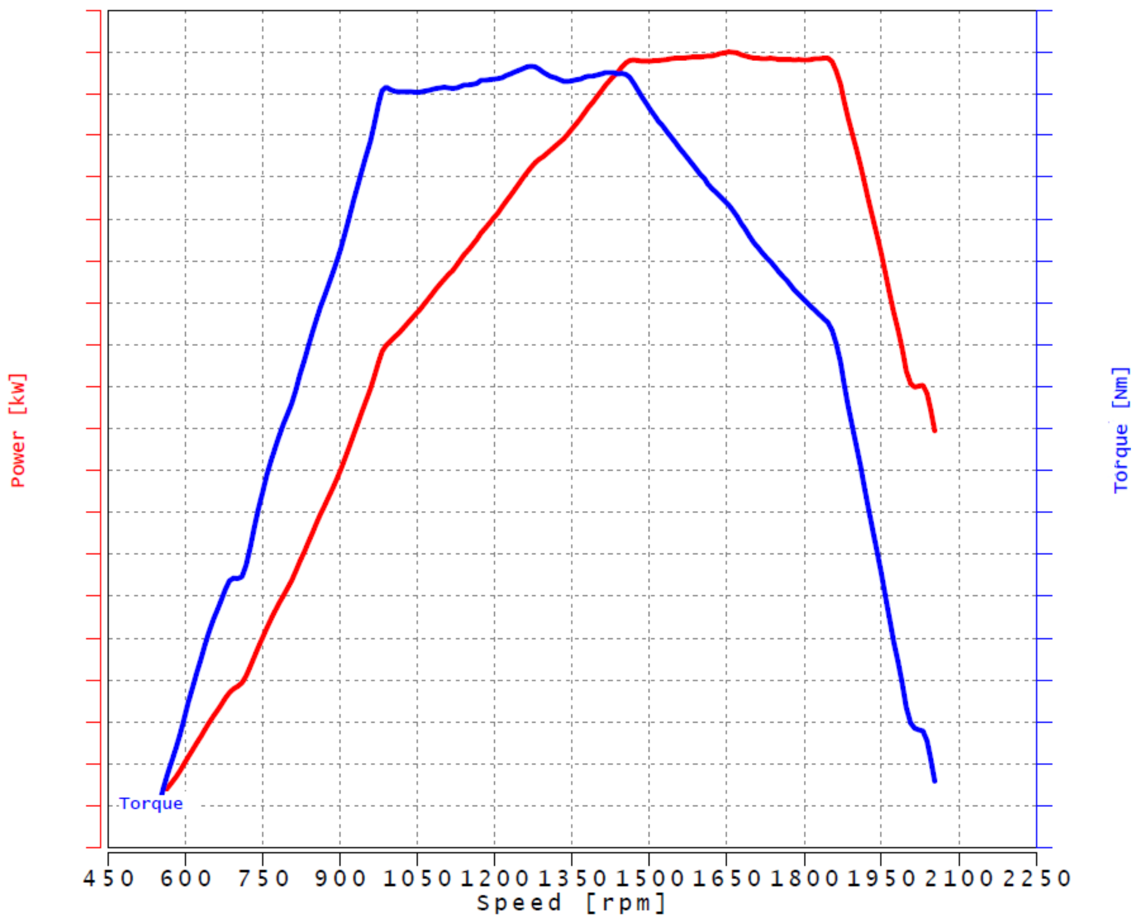

FIGURE 6.1 - FULL LOAD CURVE

6.2 WHTC test cycle result

During the WHTC test cycle the AVL software measures the value of the torque and of the speed after the de-normalization of the values given by the regulation. The WHTC is composed of a Cold Test and an Hot Test. Between these two there is a Hot Soak of 5 minutes. The influence of the cold test is 14% on the total emissions while the hot test accounts for the remaining 86%.

FIGURE 6.2 – WHTC SPEED PROFILE COLD

FIGURE 6.3 – WHTC SPEED PROFILE HOT

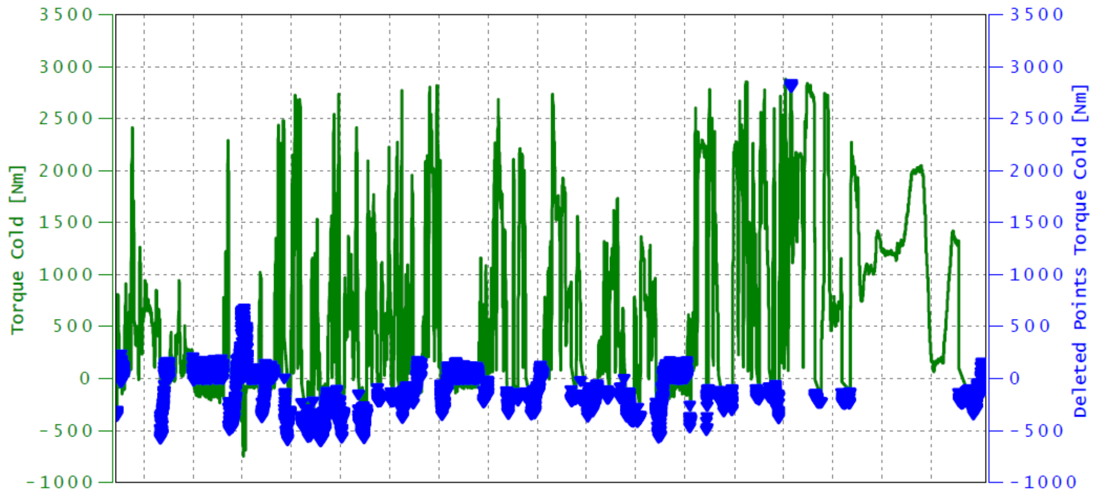

FIGURE 6.4 – WHTC TORQUE PROFILE COLD

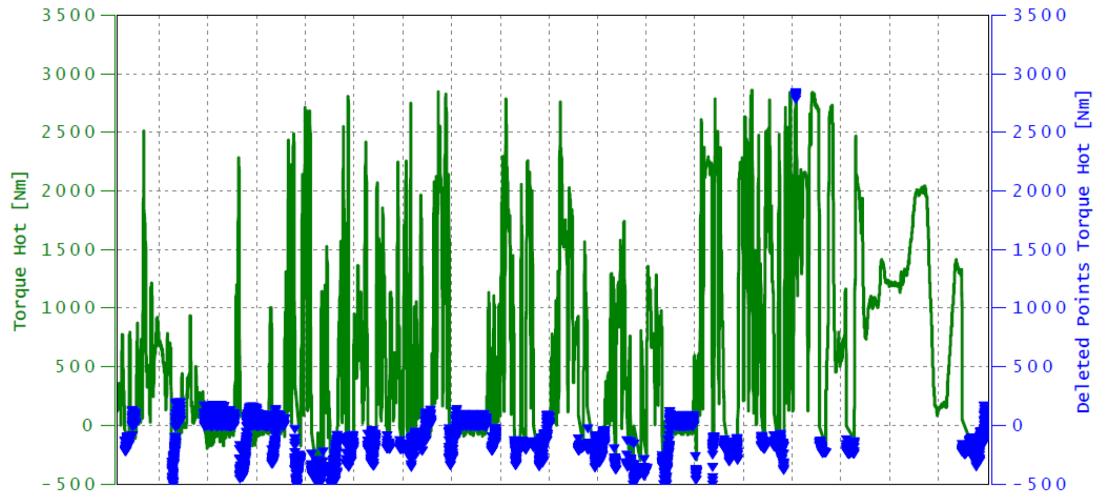

FIGURE 6.5 – WHTC TORQUE PROFILE HOT

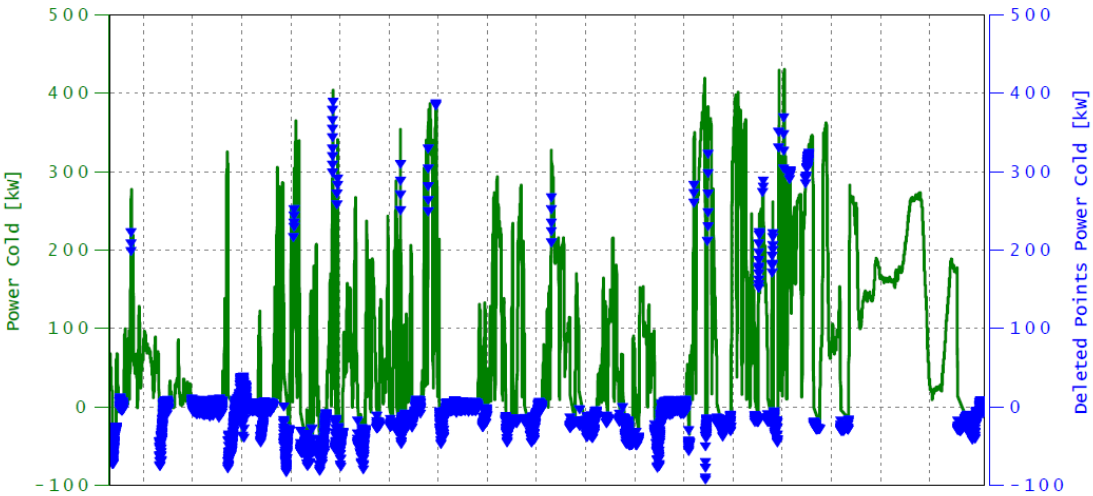

FIGURE 6.6 – WHTC POWER PROFILE COLD

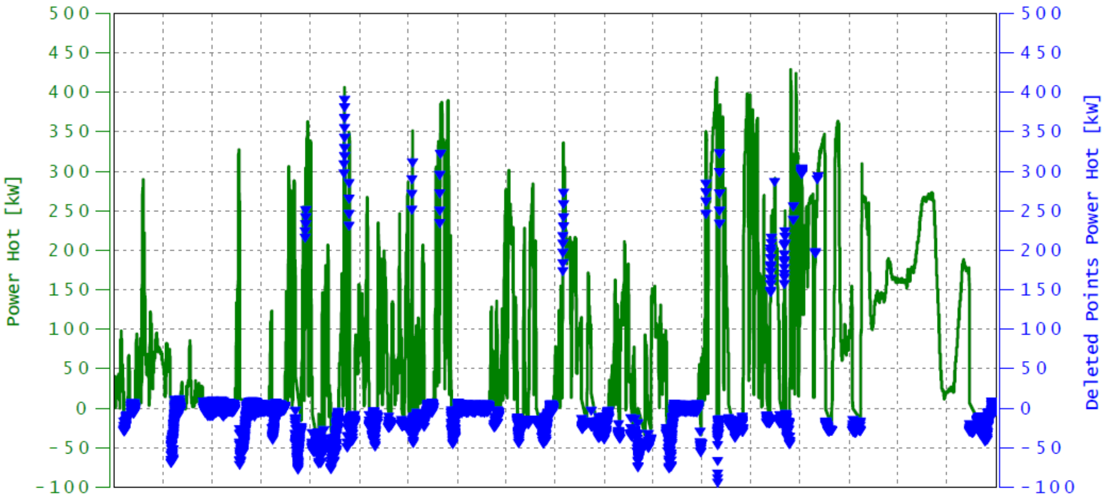

FIGURE 6.7 – WHTC POWER PROFILE HOT

During a WHTC test cycle of a diesel engine, the measured pollutants are the following: particulate matter mass (PM), particulate number (PN), carbon monoxide and dioxide (CO and CO_2), unburned hydrocarbons (HC) and ammonia (NH_3).

The equation by which the overall PM is calculated is the following:

$$PM_{tot} = \frac{PM_{test,cold} \cdot 0{,}14 + PM_{test,hot} \cdot 0{,}14}{(Energy_{cold} \cdot 0{,}14 + Energy_{hot} \cdot 0{,}86)} \left[\frac{mg}{kWh}\right]$$

It is checked that the result is lower than the PM limit of 10 mg/kWh.

6.2.1 Overall test results

In the following table there are the results of WHTC test cycle. The measured values of the pollutants are divided by the engine power, to obtain specific values.

	Unit	Value Cold	Value Hot	Status
THC	mg/kWh	10,410	40,531	Passed
NO_X	mg/kWh	713,698	186,885	Passed
CO	mg/kWh	65,522	51,490	Passed
CO_2	g/kWh	638,439	620,845	Passed
NH_3	ppm	0,089	0,169	Passed
PN	[#/kWh] $*10^{11}$	0,276	0,436	Passed

TABLE 6.2 – WHTC RESULTS

As it is reported on the results, the engine unit successfully passed the WHTC test, and the type approval procedure can continue to the next step, which is the WHSC test cycle.

6.3 WHSC test cycle result

As already explained, the WHSC test cycle is performed after a denormalization of the corrected power and torque. This is done to calculate the exact WHSC cycle that the engine should run (in terms of speed profile). The test is performed through AVL software that allows to interact with the bench. On the software, it is updated the cycle that must be run, with all the proper engine parameters. The software automatically generates the cycle that the engine will run. Here the actual torque and speed profiles are presented.

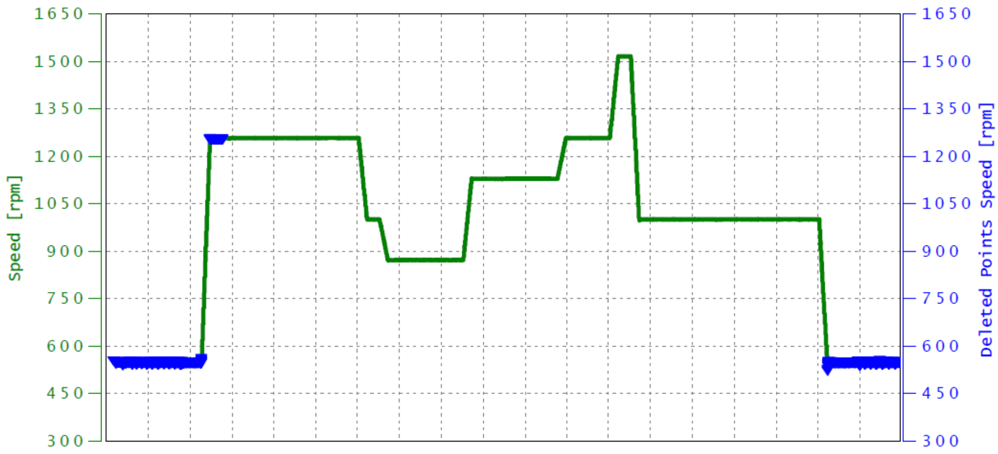

FIGURE 6.8 – ENGINE SPEED VS TIME FOR WHSC TEST CYCLE

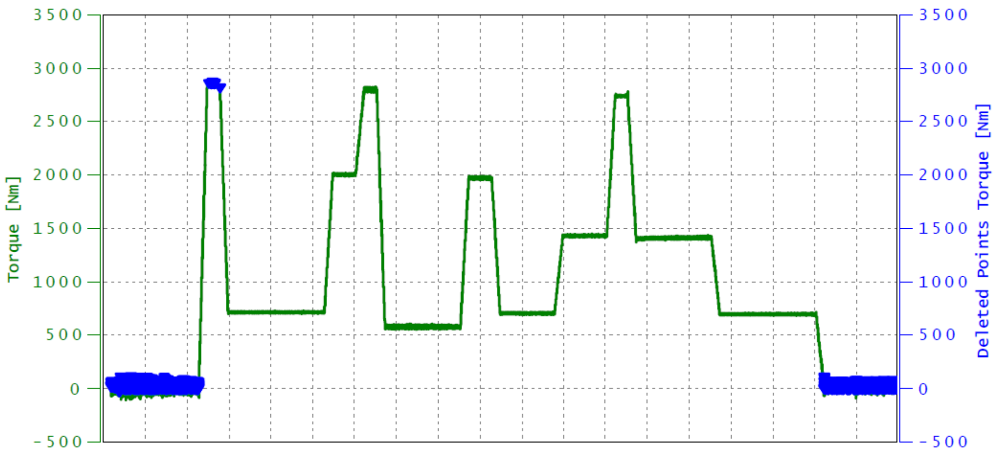

FIGURE 6.9 – TORQUE VS TIME FOR WHSC TEST CYCLE

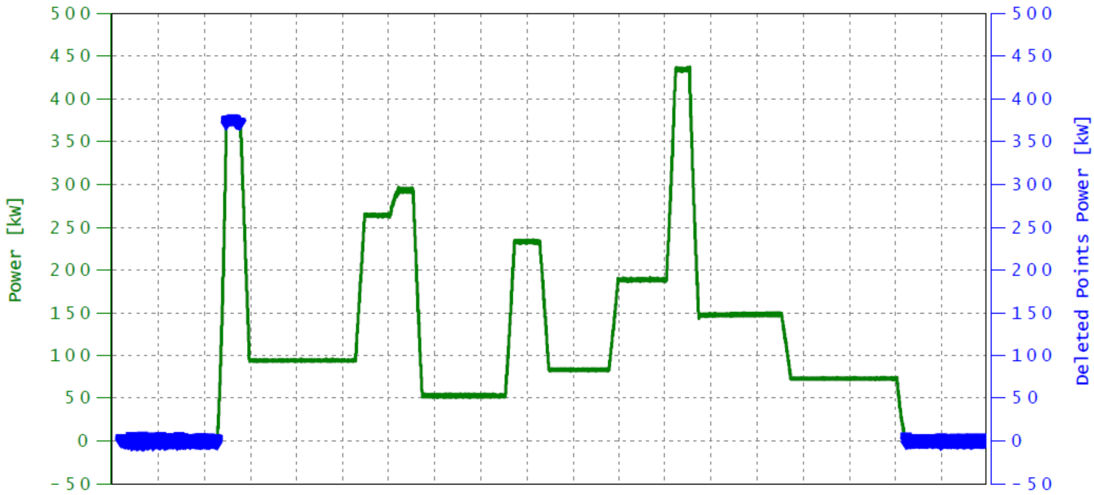

FIGURE 6.10 – POWER VS TIME OF THE WHSC TEST CYCLE

A few words on the main pollutants calculation is here reported.

The PM mass is determined by a gravimetric analyzer, using a filter that is weighted before and after the test. The PM particles are counted through a CPC device. Overall, the NH_3 emissions are checked also with the INCA software. The AVL system calculates the points of the test cycle, allows to run the cycle, and then send the report to the pc.

The PM mass weighted has to be corrected though the following equation:

$$PM_{mass,corr} = PM_{mass} \cdot \left(\frac{\left(1 - \frac{\rho_{air}}{\rho_{weight}}\right)}{1 - \frac{\rho_{air}}{\rho_{media}}} \right) \; [mg]$$

The difference between the weight of the filter before and after the test gives the PM mass emitted by the engine:

$$\Delta_{PM} = PM_{mass,corr,eng} - PM_{mass,corr,begin} \; [mg]$$

The last passage is the calculation of the PM mass emitted over the test. The value shall be then divided by the engine power since the results has to be expressed in mg/kWh.

$$PM_{test} = \Delta_{PM} \cdot (M_{exh}/(\frac{M_{diff}}{1000})) \; [mg/test]$$

6.3.1 Overall test results

In the following table there are the results of WHSC test cycle. The measured values of the pollutants are divided by the engine power, to obtain specific values.

	Unit	Limit	Value	Status	Probe
THC	mg/kWh	130	5,180	Passed	Tailpipe
NO_X	mg/kWh	400	208,303	Passed	Tailpipe
CO	mg/kWh	1500	43,103	Passed	Tailpipe
CO_2	g/kWh	N.A.	603,731	N.A.	Tailpipe
NH_3	ppm	10	0,223	Passed	Tailpipe
PM	mg/kWh	10	2,229	Passed	PSS-20
PN	$[\#/kWh]*10^{11}$	8	0,462	Passed	Particle counter

TABLE 6.3 – WHSC RESULTS

As can be noted from the table all the values fall under the limits. The engine unit successfully passed the test, and the type approval procedure can continue to the next step.

6.4 WNTE test cycle result

In this section it is reported the outcome of the worldwide harmonized not-to-exceed test, which is mandatory for type approval, and it is based on laboratory testing. The engine is asked to run on 15 specified operating points, randomly selected from three cells of the working area, composed of 5 points each. The diagrams reported below show respectively the speed and torque profile that the engine must follow.

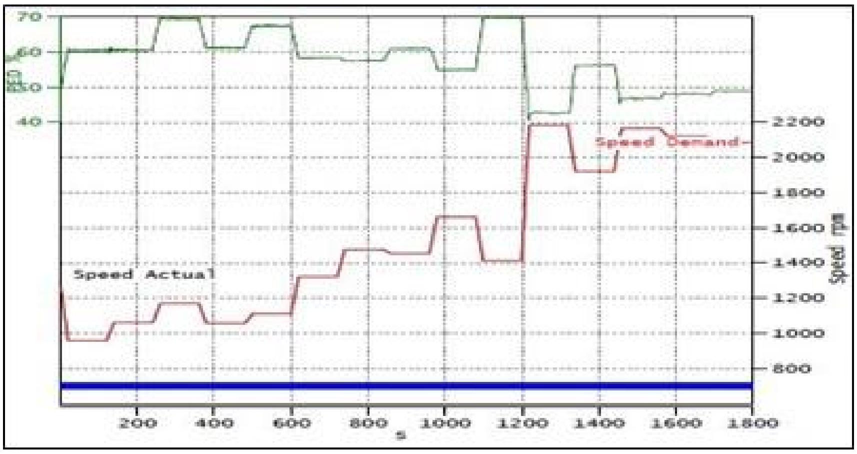

FIGURE 6.11 – SPEED PROFILE WNTE

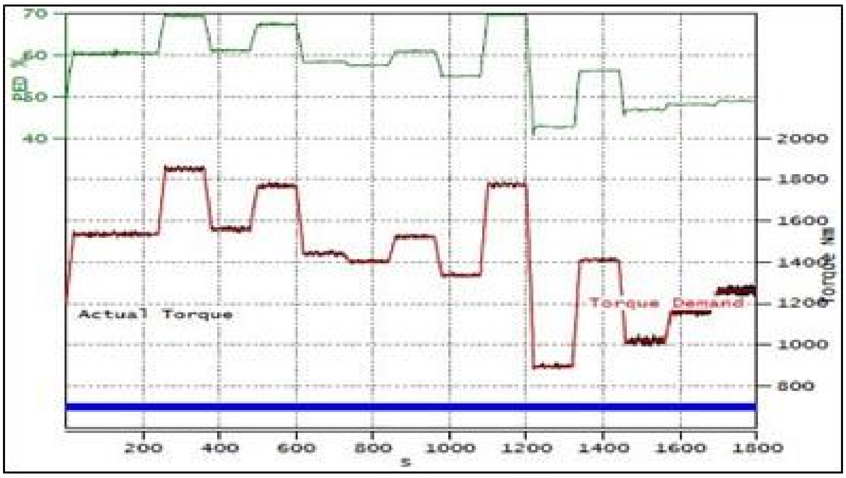

FIGURE 6.12 – TORQUE PROFILE WNTE

In the following table the results of WNTE test is reported. Even here the engine has successfully passed the test.

EMISSION LIMITS				
Legislation used for calculation		ECE-TRANS-WP29-GRPE-62-10		
Emission limit		Euro VI		
Phase 1	**Unit**	**Limit**	**Value**	**Status**
CO	[mg/kWh]	2000	15,0	Passed
NO_X	[mg/kWh]	600	119,0	Passed
THC	[mg/kWh]	220	12,00	Passed
Phase 2				
CO	[mg/kWh]	2000	11,0	Passed
NO_X	[mg/kWh]	600	103,0	Passed
THC	[mg/kWh]	220	21,00	Passed
Phase 3				
CO	[mg/kWh]	2000	17,0	Passed
NO_X	[mg/kWh]	600	236,0	Passed
THC	[mg/kWh]	220	29,00	Passed
PM	[mg/kWh]	16	1,4	Passed

TABLE 6.4 – WNTE RESULTS

7. Conformity of production (CoP) and In-service conformity (ISC)

As mentioned in the chapter related to the product development process, In-service conformity and conformity of production are two important concepts in the regulatory framework, particularly for automotive and manufacturing industries. They are basically plans that belongs to the activities of product and process validation, meant to certify the product compliance. Their scope is, indeed, to ensure that products meet specified standards both at the time of production (CoP) and during their usage lifecycle (ISC).

7.1 Conformity of production

The term “conformity of production” encompasses a series of provisions and measurement methods that the original equipment manufacturers (OEMs) uses to guarantee to certification authorities that its engines and production processes are compliant to the current legal requirements and with the emission limits for which they have been certified. Even though CoP testing isn't a mandatory requirement under every environmental regulation worldwide (it is mandatory in the EU, for instance), it's highly advisable for engine manufacturers to create and follow a CoP testing plan. This plan would help them regularly check the emissions performance of their engines and address any problems that might arise. Doing so can significantly reduce the chances of encountering non-compliance issues.

Starting from 01/01/2013 for new homologations, and from 01/01/2014 for new registrations, the Euro VI provisions are mandatory in the EU. The detailed procedures for Conformity of Production are reported in Paragraph 7 of “Annex I” of Reg. EC 582/2011, with reference to Directive 2007/46/EC. Regulation EC 582/2001 makes direct reference for some key requirements also to the correspondent ECE R. 46-06, equivalent to Euro VI.

7.1.1 CoP requirements

The conformity of production testing procedures must respect the following indications:

- Conformity of production shall be checked based on the description in the type-approval certificates;
- Three engines shall be randomly taken from the series production of the engines under consideration;
- all engine components must be taken into consideration, including ATS, even when the component is supplied by a third company;
- Engines shall be subjected to testing on the WHTC, and on the WHSC if applicable, for the checking of the production conformity;
- The limit values are the ones set out in Annex I to Regulation (EC) No. 595/2009;
- The measured emission of the gaseous and particulate pollutants from engines subject to checking for conformity of production shall be adjusted by application of the appropriate deterioration factors (DF) for that engine as recorded in the Addendum to the EC type-approval certificate.

In the following picture it is reported the Euro VI conformity testing activities.

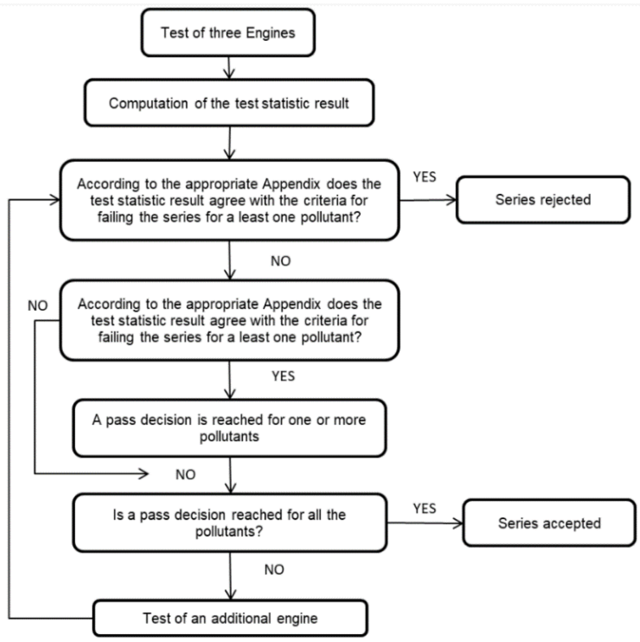

FIGURE 7.1 - COP TEST PROCEDURE

7.1.2 How to perform CoP

The first requirement is to ensure that a sample of engines produced at each manufacturing plant undergoes CoP emission tests equivalent to those required for emission certification. This involves:

- WHSC and WHTC test cycles for on-road vehicles.
- Using fuel that meets the legal specifications for the engine (if different fuels are available, use the one that is worst from an emissions standpoint).
- Testing the correct numbers of each engine family.

This ensures that the engines being produced comply with the certified emission limits and provides early detection of any emission-related production issues (such as drift), reducing the risk of legal action, the costs of engine or vehicle recalls, and potentially severe financial penalties. Merely defining a percentage of engines to be tested in any given model year does not minimize the risk of non-compliance with emission regulations. This is because the cumulative risk depends on:

- The number of units produced since the last emission test (potentially non-compliant engines produced, affecting both legal enforcement costs and the number of affected customers).
- The amount of manufacturing deviation that can occur before exceeding the emission limit (related to the margin between certification values and legal limits, and the sensitivity of the engine to manufacturing changes).
- The likelihood that an error has caused an undesired change in the manufactured product (most likely during changes to manufacturing processes, specifications, or suppliers).

Each manufacturer can decide how many engines to test. Some establish higher testing rates at the start of production (over 1%), while typical mature test rates are 0.3-0.5% of total production. Some countries are progressively setting a minimum test rate (e.g., Brazil at 0.4%).

Who is responsible for CoP?

The engine manufacturer is legally accountable for CoP testing of its own products. The plant quality oversees performing CoP testing according to the annual CoP Test Plan decided by the product conformance division. Still plant quality, at the end of the test, must deliver the CoP test reports to the department of product conformance. An important role is covered by both product engineering and FPT quality and product behavior departments. They are in charge of giving support every time a CoP test fails, and a root cause analysis needs to be performed, using some problem-solving techniques [18].

Where CoP testing should be performed?

All engine manufacturing plants should have a proper Control Plan in place, in which the CoP testing should be substantially included. There's no specific requirement to perform CoP testing directly at the production plant facilities, although it's highly recommended.

When CoP testing should be performed?

Annually: routine testing of current production products, under current certificates still in production. Service (Intermittently): select testing through product life after certificates have expired covering post-production running changes.

Why CoP testing should be performed?

- Quality Assurance: Ensures consistent quality and performance of products;
- regulatory compliance: Aligns with regulatory requirements to ensure products are safe, reliable, and environmentally compliant;
- auditing and testing: Regular audits and tests are conducted on production samples to verify that they meet the required standards;
- documentation: Manufacturers must maintain detailed documentation and records of the production process, test results, and quality control measures [.

7.2 In-Service Conformity

In-Service conformity (ISC) is a term that refers to the evaluation of products after they have been released to the market and are in use by the consumers to ensure that they continue to meet regulatory standards throughout their operational life. In this case study, the product is an heavy-duty diesel engine, so the evaluation refers to the check of the emissions of the main engine pollutants (such as CO, HC, CH_4, NO_x, and PN), ensuring that they falls within the limits set by the current regulation. ISC is a legal obligation, mandatory for all the engine manufacturers, which has been in place since the beginning of Euro VI standards (2013 new type approvals, 2014 new registrations). The testing activities consist basically of performing road tests, which are called PEMS. The acronym stands for Portable Emission Measurement System but in this case, it is used also for indicating the testing activities that must be performed on the road, in real driving conditions. ISC testing is required within 18 months of the first registration, on a vehicle registered in Europe that has accumulated a minimum of 25,000 km [13]. For European on-road heavy-duty trucks and bus engines, PEMS testing is used during type-approval and in-service conformity. The differences between type-approval and ISC are primarily in the type of vehicle that is tested, the payload and the accumulated mileage. On the following table the requirements of ISC are summarized [35].

	Type-approval (OCE)	**In-Service conformity**
Payload	50-60% payload	10-90% payload
Vehicle	Prototype or modified production vehicle	Production vehicle
Min. accumulated use	Not specified	25,000 km
Atmospheric pressure	$P_{atm} \geq 82.5$ kPa	
Ambient pressure	$T_{atm} \geq -7°C$ and $\leq 0.4514 \cdot (101,3 - P_{atm}) + 311$ K	
Coolant temperature	$\leq T_{atm} + 5°C$ and $\leq 30°C$	

TABLE 7.1 – PEMS TESTING BOUNDARY CONDITIONS*

* table is taken from the article “EU: Heavy-Duty Truck and Bus Engines: OCE and ISC PEMS Testing” available at www.dieselnet.com

7.2.1 ISC testing requirements

In-Service Conformity (ISC) testing must be performed biennially for each engine family. Manufacturers may request to discontinue testing five years post-production. The number of engines tested for ISC varies from 3 to 10, depending on cumulative test outcomes. The sampling method aims to determine the count of nonconforming engines, with defined pass/fail criteria. The procedure is designed to ensure a 90% chance of passing a batch with 20% defective engines (producer's risk = 10%), and a 10% chance of accepting a batch with 60% defective engines (consumer's risk = 10%). A fail decision can be reached with just three engines tested, but passing requires additional testing, up to a total of 10 engines, ensuring the number of nonconforming engines does not exceed the allowable threshold [35].

7.2.2 PEMS testing

PEMS testing encompasses urban (0-50 km/h), rural (50-75 km/h), and motorway (>75 km/h) driving conditions, with the proportion of these segments varying by vehicle category. The segments can be identified using geographical coordinates (via a map) or the first acceleration method. For evaluating the trip composition, calculate the duration of each segment starting from when the coolant temperature first reaches 70°C or stabilizes within ±2°C over five minutes, whichever occurs first, but no later than 15 minutes after engine start. The period needed to reach 70°C should be conducted under urban driving conditions. The distribution from the World-Wide Harmonized Heavy-Duty Certification (WHDC), Global Technical Regulation (GTR) No. 4 database, may be used to guide the trip evaluation [35]:

- Accelerating time: 26.9%;
- Decelerating time: 22.6%;
- Cruising time: 38.1%;
- Stop (vehicle speed = 0) time: 12.4%.

The test duration should be long enough to complete between four and eight times the work done during the WHTC or produce four to eight times the CO2 reference mass (in kg/cycle) from the WHTC, if practicable. If the Diesel Particulate Filter (DPF) undergoes a non-continuous regeneration event during the trip or if OBD malfunctions occur during the test, the manufacturer can void [35].

Emission evaluation

For engines up to and including Euro VI-D, emissions from cold starts (when coolant temperature is below 70°C) are excluded. However, for Euro VI-E engines, a portion of the cold start emissions is included, with the exception of emissions when the coolant temperature is below 30°C. Data evaluation starts once the coolant temperature reaches 70°C for Euro VI-D and earlier engines, or 30°C for Euro VI-E engines, or once the coolant temperature stabilizes within ±2°C over a period of 5 minutes, whichever occurs first, but no later than 10 minutes after the test begins. Emissions are averaged using an "averaging window," a moving average process where the period of the averaging window is based on the mechanical work or CO2 emissions measured during the WHTC test in type approval testing. In the work-based method, the reference work (Wref) is the work (kWh) produced by the engine over the WHTC. In the CO2-based method, the reference CO2 (mCO2, ref) is the CO2 mass (kg) measured over the WHTC. The window lengths during data evaluation correspond to the time required to produce the reference work or reference CO2 mass and can vary during the test depending on the engine's average power output. After parsing the data into averaging windows, valid windows are identified [35].

Valid work windows

For engines up to and including Euro VI-C, valid work windows are those where the average power is more than 20% of the maximum engine power (Pmax). At least 50% of the windows must be valid. If this threshold is not met, the power threshold is lowered by 1% increments until the valid windows percentage reaches 50%, but it must not go below 15% of Pmax. If less than 50% of the windows are valid at 15% of Pmax, the test is considered void. For Euro VI-D and newer engines, valid windows require the average power to exceed 10% of Pmax. The test is void if less than 50% of the windows are valid or if there are no valid windows in urban-only operations after applying the 90th percentile rule. This rule ensures urban driving's impact on NOx emissions is reflected in the test results. Conformity factors are calculated for each valid work window and each pollutant individually [35]:

$$CF = \frac{e}{L} \qquad (1)$$

where:

e = the brake-specific emission of the gaseous pollutant (in mg/kWh) or PN (in #/kWh);

L = the applicable limit (in mg/kWh) or (#/kWh)[35].

Valid CO_2 windows

For engines up to and including Euro VI-C, valid CO2-based windows are those whose duration does not exceed the maximum calculated using the following formula:

$$D_{max} = \frac{3600 \cdot W_{ref}}{0{,}2 \cdot P_{max}} \qquad (2)$$

where:

- D_{max} is the maximum window duration in seconds;
- P_{max} is the maximum engine power in kW [35].

If fewer than half of the windows are valid, the data evaluation needs to be repeated using longer window durations. This involves adjusting the parameter 0.2 in increments of 0.01 until the percentage of valid windows reaches at least 50%, but not reducing it below 0.15. If less than 50% of the windows remain valid even at the maximum window duration, the test is considered invalid. For Euro VI-D and subsequent engines, valid windows are those whose duration does not exceed the maximum calculated using the same formula (3). Conformity factors for each valid window and pollutant are then computed as follows [35]:

$$D_{max} = \frac{3600 \cdot W_{ref}}{0{,}1 \cdot P_{max}} \qquad (3)$$

$$CF = \frac{CF_1}{CF_C} \qquad (4)$$

$$CF_1 = \frac{m}{m_{CO2}(t_{2,i}) - m_{CO2}(t_{1,i})} \qquad (5)$$

$$CFc = \frac{m_L}{m_{CO2,ref}} \qquad (6)$$

where:

- CF_1 is the in-service ratio;
- CF_C is the certification ratio;
- m is the mass emission of the gaseous pollutant (mg/window) or particle number (#/window);
- $m_{CO2(t2,i)} - m_{CO2(t1,i)}$ = the CO2 mass during the i^{th} averaging window (kg) and $t_{1,i}$ and $t_{2,i}$ are the being and end times respectively of the i^{th} window;
- m_L = the mass emission of the gaseous pollutant or PN corresponding to the applicable limit on the WHTC (mg) or (#) respectively.

Final conformity factor

For Euro VI-E engines, the final conformity factor (CF_{final}) for each pollutant using either the work-based or CO2-based method is [35]:

$$CF_{final} = 0.14 \cdot CF_{cold} + 0.86 \cdot CF_{warm} \qquad (7)$$

where:

- CF_{cold} is the conformity factor of the period of cold operation of the test, which shall be equal to the highest conformity factor of the moving averaging windows starting above 30°C and below 70°C coolant temperature;
- CF_{warm} is the conformity factor of the period of warm operation of the test, which shall be equal to the 90th cumulative percentile of the conformity factors.

Up to and including Euro VI-D engines, the final conformity factor is the 90th cumulative percentile of the conformity factors calculated with either Equation (1) or Equation (4). These exclude data for engine operation below 70°C [35].

Pre/post test procedure

Let us see some practical measures and provisions to adopt when performing the on-road testing. Here are summarized the first activities to do:

- Starting and stabilizing the PEMS instruments;
- cleaning the sampling system (purging cycle);
- leakage test;
- checking and calibrating the analyzers: the zero and the span calibration and the linearity checks of the analyzers shall be performed using calibration gases;
- remove condensation and diesel particulate matter from the pressure lines and the associated flow tube measurement ports.
- vehicle storage: it could be dangerous (rain, low/high ambient temperatures) for equipment parking the vehicle outside the workshop;
- before starting the operation, it is mandatory the verification of bottles pressure and possible leakages, the back-up batteries charge and generator refueling, the PEMS equipment and accessories fixing. The network connections between PEMS and PC should be stable and far from possible interferences with vehicle's parts/object. Any interference between heated sample line/flow pipes and vehicle's hot/moving parts should be avoided and the part of PEMS equipment at the interior of the vehicle well fixed and without interference with driver.

Test paths

Depending on the vehicle classes, there is essentially one test route approved by the Authority (C.P.A.) that can be used for all vehicle classes. The only modification needed is the length of the individual segments (urban, rural, and highway) to meet the legally required proportions. The routes are depicted in the following images.

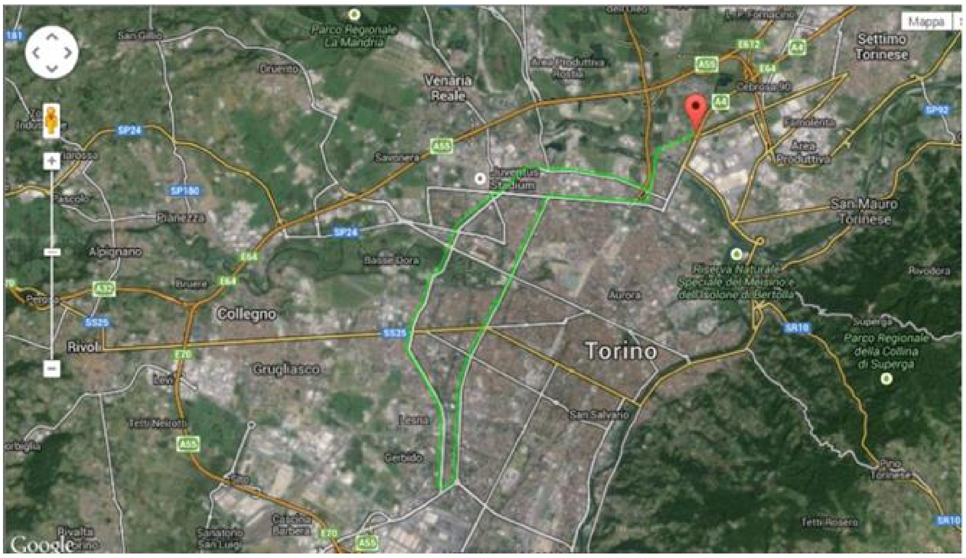

FIGURE 7.2 – URBAN

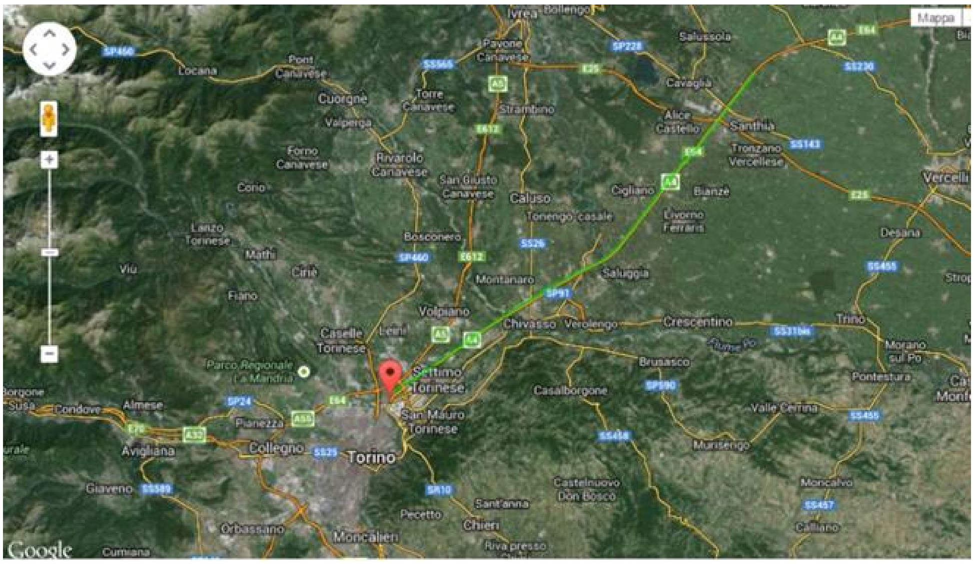

FIGURE 7.3 - RURAL

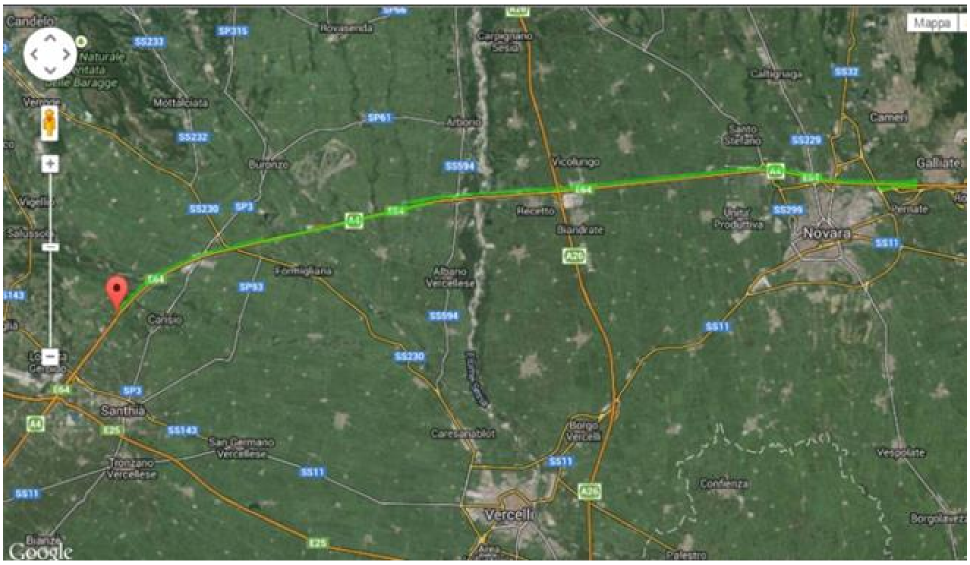

FIGURE 7.4 – MOTORWAY

Results

The test results are shown in the tables below. The total trip duration is 8067 seconds. The total work produced is 198.2 kW/h. The ECU measured a total distance of 152.2 km, compared to the GPS measurement of 147.6 km. The numerical results indicate that the test has passed (specific results cannot be disclosed).

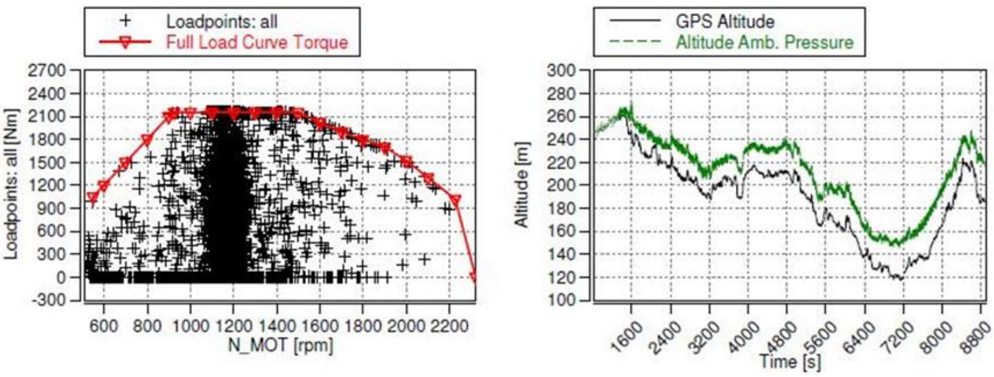

FIGURE 7.5 – LOADPOINTS VS RPM AND ALTITUDE VS TIME

	CO	THC	NMHC	CH4	NOx	PM
Pass-fail results	passed	passed			passed	passed
Work window conformity factor	0.12	-0.06	n/a	n/a	0.53	0.00
CO2 mass window conformity factor	0.12	-0.07	n/a	n/a	0.60	0.00

Trip Information	Urban	Rural	Motorway
Shares of time of the trip in % characterised by urban, rural and motorway operation as described in point 4.5 of Annex II to Regulation (EU) No 582/2011	20.5	28.8	50.7

Shares of time of the trip in % characterised by accelerating, decelerating, cruising and stop as described in point 4.5.5 of Annex II to Regulation (EU) No 582/2011		
Accelerating	8.3	%
Decelerating	7.7	%
Cruising	79.3	%
Stop	4.7	%

	Minimum	Maximum
Work window average power (%)	20.4	41.4
CO2 mass window duration (s)	944.0	1675.0

Work window: percentage of valid windows	86.1
CO2 mass window: percentage of valid window	83.4
Fuel consumption consistency ratio	m = 0.86
	r² = 0.93

FIGURE 7.6 - PEMS TESTING RESULTS

7.3 Importance of ISC and CoP

Both Conformity of Production and In-Service Conformity play vital roles in:

- consumer safety: guaranteeing that products are safe for use from the point of purchase and throughout their entire lifespan;
- regulatory compliance: meeting national and international regulations to prevent legal issues;
- brand reputation: upholding a positive brand image by consistently providing high-quality and reliable products;
- environmental protection: ensuring products maintain their performance over time without negatively impacting the environment, such as through increased emissions.

In essence, CoP verifies that products meet required standards at manufacturing, while ISC ensures these standards are met during the product's operational life.

8. Product support and monitoring

Together with the activities of the product and process validation (including homologation and conformity of production), another important phase of the product development process is the program closure. This is the moment when the engine has already launched in the market, and it is running in field. Typically, during this phase, the engine manufacturer provide support to the customer by launching specific programs or by activating special processes. Among them there are the Early Warning Team process (EWT), and the tutorship program that will be here explained.

8.1 Early Warning Team process

The early warning team is a task force of people that can be established for the new engines launched on the market. The aim is to closely monitor the performance and the quality of the engines early in their product lifecycle. The team is crucial for identifying and addressing any issues that arise in the engine, with the goal of ensuring reliability and satisfaction of customers, so maintaining the company's reputation.

8.1.1 Scope of the EWT

The early warning team can apply to all the products whose classification in the development process requires its activation. In case of activation, their activities are carried out from the Start of Production (SOP) for a period that can go from six months up to a maximum of one year. Anyway, the EWT closure is subject to the completion of faults found during the observed period. When EWT is closed, for all the faults found on the engine, a sustainable solution must be found as well as an implementation plan. After that, the problems are transferred to the professional figures dedicated to the current production.

8.1.2 Team composition

The team typically includes experts from various departments such as:

- quality assurance: to ensure that engines meet all required standards and specifications;
- product behavior: to monitor how the engines perform in real-world conditions and gather data on any deviations or issues;
- engineering: to provide technical expertise and solutions for any identified problems;
- customer support: to receive and analyze feedback from customers and service centers

8.1.3 Activities and responsibilities

- Monitoring and data collection: collecting in real time data from engines in field, including performance metrics, emission data, and any fault codes. Gathering feedback from customers, service centers, and sales teams about the engine's performance and any issue encountered;
- analysis and reporting: analyzing the collected data to identify trends, recurring issues, and potential areas of concern. Compiling reports on engine performance, highlighting any deviations from expected behavior;
- issue identification and resolution: prioritizing issues based on their severity, frequency, and impact on customers. Collaborating with engineering and manufacturing teams to diagnose and resolve problems. Implementing corrective actions which can include design modifications, process improvements or software updates;
- communication and feedback: keeping all the stakeholders informed about the status of engines and any identified issues. Providing feedback to the design and development teams for future improvements;
- preventive measures: using insights gained from early warning activities to anticipate and prevent potential problems in future engine design. Incorporate testing and quality control procedures to make lessons learned.

8.1.4 Benefits

- Improved Product Quality: by identifying and addressing issues early, the team helps ensure that the engines perform reliably and meet customer expectations;
- customer satisfaction: promptly resolving issues enhances customer trust and satisfaction;
- cost savings: early detection and resolution of problems can prevent costly recalls and warranty claims;
- continuous improvement: feedback and data from the early warning team contribute to ongoing improvements in engine design and manufacturing processes.

8.2 Tutorship program

The primary goal of the Tutorship program is to provide ongoing, dedicated support for new engines after their launch. This involves ensuring long-term performance and quality by closely monitoring the engines and providing continuous feedback and improvements. The Early Warning Team is similar to the tutorship, but it is focused on quickly identifying and addressing any immediate issues that arise shortly after the engines are launched. The objective is to catch and resolve problems early to prevent widespread issues and maintain customer satisfaction. So, while EWT is based on an immediate detection and resolution of issues that could arise shortly after the launch, the tutorship looks a bit more in the long-term perspective.

8.3 Defect reporting

The activity of monitoring a product takes place directly on the vehicle, through the On-Board Diagnostic (referred as OBD). OBD represents all the electronics installed on the vehicle responsible for reporting malfunctions or failures of the devices installed on it. The errors collected by the OBD are meant to be read by the operators of a workshop that take care of the repairs. Usually, after a defect detection, the driver goes to the dealership. Here the workshop checks where the failure is and, if needed, replaces the broken components. At this point of the operation, if the vehicle falls under the warranty period, the manufacturer pays the repair, and the dealer produces and send a report to the quality department.

These kinds of reports are called "claim", and they contain a lot of information regarding the specific problem detected by the dealer. The most important data are:

- Vehicle identification number;
- engine serial number;
- type of vehicle;
- customer;
- working hours/km at the failure;
- part number of the replaced component;
- warranty type;
- repair date;
- homologation class of the engine;
- error code;
- list of payments;
- dealer comment.

When we talk about product behavior, the most important word is "monitoring". The activity of tracing the phenomena that affect the product quality needs some metrics, i.e. some specific indicators, that describe the performance of a product in a measurable way. These are failures and costs. Failures are evaluated during the warranty period and the indicator, called F100, is given by the number of claim related to the parts that has been replaced and the total units in service in the observed period:

$$F100 = \frac{n^\circ\ of\ claim}{total\ units} \cdot 100$$

Cost, instead, are used as indicators to consider the economic performance of the company. The indicator is called ACPU (Average Cost Per Unit) and is defined similarly to the F100 but having the total spend of the replaced parts on the numerator:

$$ACPU = \frac{Total\ cost\ of\ replaced\ parts}{total\ units}$$

By reading the comments contained in the claims, it is possible to better understand the importance of each problem, clarifying also if the problem is actually related to the replaced part. An instrument that is used to trace which is the most critical component within a list, in terms of ACPU and F100, is the pareto analysis. Pareto diagram allows to identify the most critical component both in term of failure rate and in terms of spending, helping to decide whether to attack it or not.

When the top issues are identified, the quality manager analyses the failure to identify the root cause and to find a sustainable solution that must then be implemented. The analysis can take place from supplies, in plant (directly analysing the replaced component that has shipped back to the manufacturer) or in field.

In general, the target of quality and product behaviour is to reduce the problems occurring on the product in use, ensuring reliability and security. This promotes the quality as the cornerstone of a successful company

9. Conclusions

This thesis has explored the comprehensive homologation process of a new diesel engine designed for heavy-duty on-road applications, developed in collaboration with FPT Industrial. The focus was on adhering to the stringent EURO VI step E emission regulations. Through this detailed analysis, several critical conclusions can be drawn.

Firstly, the overview of the main pollutants and their impact on human health and the environment has underscored the necessity for rigorous emission standards. The analysis of emission regulation in EMEA market region, highlights the effort towards minimizing vehicular emissions and its paramount importance.

The detailed examination of the EU's emission standards for heavy-duty vehicles and the future CO2 emission targets illustrates the progressive tightening of regulations aimed at reducing environmental impact. These stringent norms necessitate the integration of advanced technologies in engine design and calibration processes. The study has shown that FPT Industrial has successfully incorporated high technological content and innovative strategies into their engine and after-treatment system, which is pivotal for meeting current emission standards.

The homologation process, involving specific dyno tests (WHSC, WHTC, and WNTE) and real driving condition tests using Portable Emissions Measurement Systems (PEMS), is critical for type approval and in-service conformity (ISC). This thorough testing regimen ensures that the engines not only comply with the regulatory requirements at the point of production, but also maintain their emission performance throughout their operational life. Furthermore, Conformity of Production (CoP) tests post-market launch is essential for ongoing performance monitoring, reinforcing the importance of continuous compliance and environmental stewardship.

Beyond regulatory compliance, this thesis emphasizes the importance of customer satisfaction, production stability, and performance in the immediate post-launch phase. The Early Warning Team process and the tutorship program have been highlighted as effective strategies for promptly addressing and resolving quality issues during the initial market phase. These initiatives are crucial for maintaining high customer satisfaction and ensuring the reliability and performance of new engines.

In conclusion, this thesis provides a comprehensive understanding of the homologation process for heavy-duty diesel engines, emphasizing the importance of technological innovation, stringent testing, and continuous quality improvement. The findings underscore FPT Industrial's commitment to regulatory compliance, environmental protection, and customer satisfaction, setting a benchmark for the industry in developing high-performing, reliable, and eco-friendly diesel engines.

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