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Setup and validation of a pre-prototype aftertreatment system aimed to reduce PM2.5 and NO_x emissions from locomotive diesel engines

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Abstract

In the ENSPIRIT FP7 European project framework a locomotive diesel engine aftertreatment pre-prototype, due to real-world testing difficulties, was realized directly downscaled and adapted for an automotive emissions laboratory testing. It is here reported how its NO_x and PM2.5 abatement capabilities were determined testing two diesel engine passenger cars deprived of all abatement systems. With the first car the setup and performance of the ENSPIRIT® pre-prototype were optimized using several analyzers, even providing size distributions of ultrafine particles: final emission reductions, calculated in g/bhp-hr, of NO_x by ~90% and of PM2.5 by ~60% were reached. The pre-prototype NO_x and PM2.5 abatement capabilities were then validated with the second car and results have been compared with the ones from U.S. EPA Tier 4 non-road emissions standard. It was found a NO_x emission reduction by ~90% and by ~50% for PM2.5, confirmed as statistically significant by applying the Student's t-test.

Keywords: NO_x; PM2.5; locomotive diesel engines aftertreatment; Tier 4; passenger cars; chassis dynamometer testing.

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1. Introduction

Nitrogen oxides (NO_x) cause a wide variety of health and environmental impacts as they also react with different compounds to create harmful derivatives in the family of nitrogen oxides. Exposure to particulate matter (PM) is hazardous too, particularly for children and for the elderly with health problems as particles smaller than 10 micrometers in diameter (PM10) can get deep into the lungs and some, typically within PM2.5, may even get into the bloodstream.
Diesel locomotives are significant contributors to air pollution, in terms of NO_x and PM emissions, especially in some areas like cities rail yard and seaport though, according to the European Environment Agency (2011), NO_x and PM emissions from the rail sector account for only 1–1.5% of the total emissions from all transport sectors. Jeong et al. (2017) found high concentrations of diesel exhaust can be surprisingly measured into the coaches, pointing out that even passengers are being exposed to elevated level of diesel exhaust in diesel-powered pull-trains. The current – Tier 4 (US) / Stage IV (EU) – and especially the future more and more stringent emission limits and fuel-saving requirements for non-road engines, in particular for the rail sector, require further research and investments on both engine and aftertreatment technologies. Compared to the Tier 0, especially NO_x and PM emissions reduction by about 70%, is required by US Tier 4 for engines above 560 kW, leading to 0.03 *g/bhp-hr* for PM and 1.3 *g/bhp-hr* for NO_x, as reported in EPA-420-R-98-101 (1998).
Though the newly emissions abatement technologies will be reasonably applied to railway applications in the future, it is important to point out that most of them have been tested in automotive applications only, therefore their effectiveness in locomotive applications may still be an open point. From this perspective, the combined use of automotive technologies, such as EGR + SCR + DPF, applied to the rail diesel engine sector has brought some benefits especially for PM emissions abatement, being EU stage IV compliant, whereas reduction of NO_x emissions still represents a challenge task, as mentioned in Konstandopoulos et al. (2015).
While a transfer of technologies from the road sector to the non-road mobile machinery (NRMM) usually occurs, the ENSPIRIT project (http://www.enspirit.eu/) was originally developed to employ innovative technologies not previously used by automotive applications, aiming to find the best NO_x and PM2.5 emission reductions from diesel engine exhaust, without using urea. Considering the differences between locomotive engines (large and slow) and PCs/LCVs diesel engines (small and fast), developing a specific driving cycle to test experimental vehicles, following as much as possible the structure of the Locomotive Test Cycle, was considered useful for both the pre-prototype testing phase to change and scale the system to optimize its effectiveness, and the validation phase to definitely verify the achievement of percentage emissions reduction project objectives. This also allowed to verify and obtain a good representativeness of engine's rotations per minute and exhaust flow progressions as well as in terms of NOx and PM scaled-down car emissions compared to locomotive diesel ones. The development of the driving cycle and its representativeness in accordance with railway emission's legislation is discussed in Casadei and Maggioni (2016).
The concept vision was, once the ENSPIRIT goals obtained and demonstrated, the development of a new aftertreatment product suitable for locomotives and easily fitted on diesel locomotives through the pre-prototype scaling up, whose performances had been previously tested in conditions similar to the actual testing conditions required by the locomotive emissions regulations.
This project lasted about two years, during which the pre-prototype was projected, dimensioned and realized to be suitable for 2.0 liters diesel engines passenger cars. The testing of the ENSPIRIT® pre-prototype entailed two steps: the first one, referred to as Testing Phase, was needed to find the best set-up of the pre-prototype, in order to optimize its NO_x and PM2.5 abatement capability and the second one, referred to as Validation Phase was necessary to verify and validate the effectiveness of the pre-prototype in reducing NO_x and PM2.5 emissions Testing and Validation phases were the final phases of the Project and they were, carried out at Innovhub-SSI, Automotive Emissions Laboratory (here named LEA), equipped with a chassis dynamometer suitable for LCVs emission testing.

2. Materials and methods

To assess, optimize and validate the ENSPIRIT® pre-prototype's emissions abatement capabilities several tests on the chassis dynamometer have been carried out with two 2.0 l Euro 4 diesel vehicles: a VW Golf 1.9 TDI and an Alfa Romeo 159 JTD.
The preliminary disabling of all VW Golf 1.9 TDI and Alfa Romeo 159's aftertreatments – Oxy catalyst, DPF and EGR, and ECU remapping (From EURO 4 to EURO 0) – was useful to transform the experimental vehicles in really high emitter vehicles simulating the worst emission conditions achievable for diesel passenger cars (ideally similar to diesel locomotive engines). After modifying the vehicles, it was verified the emission values

to be stable and repeatable for both Testing and Validation phases, carried on respectively with the VW Golf 1.9 TDI and the Alfa Romeo 159 JTD.
The VW Golf was initially tested to find what pollutant species could have been detected in order to both best investigate the ENSPIRIT® effectiveness in emissions reduction and obtain g/bhp-hr data to be compared with those reported by Tier 4 emission limits.
Every parameter, such as vehicles' stability conditions, chassis dynamometer calibration, temperature and humidity conditions were checked before beginning the testing phase.
The equipment used to execute the test program is represented in Fig. 1 within the sampling scheme of the Automotive Emission Laboratory (LEA) and it is described as follows:

- Chassis dynamometer system (BOSCH) with electrical simulation of inertia and braking (API-COM);
- Driver-aid 305 system (AVL);
- Constant Volume Sampler (CVS) – Constant Flow Venturi (CFV) system with a dilution tunnel (API-COM);
- Exhaust gas analysis system (AVL AMAi60);
- Automated system for test execution and data acquisition (AVL i4L);
- Speed controlled vehicle cooling fan (API-COM);
- TSI EEPS (Engine Exhaust Particle Sizer) is a high-performance instrument designed specifically for detecting particles emitted from internal combustion engines, measuring particle number in the electrical mobility diameter range of 5.6÷560 nm;
- AVL MSS (Micro Soot Sensor) used to measure PM soot fraction (as mg/m^3);
- Thermo Fisher FT-IR (Fourier Transform Infrared Spectroscopy) mainly used to measure unregulated pollutant gaseous species;

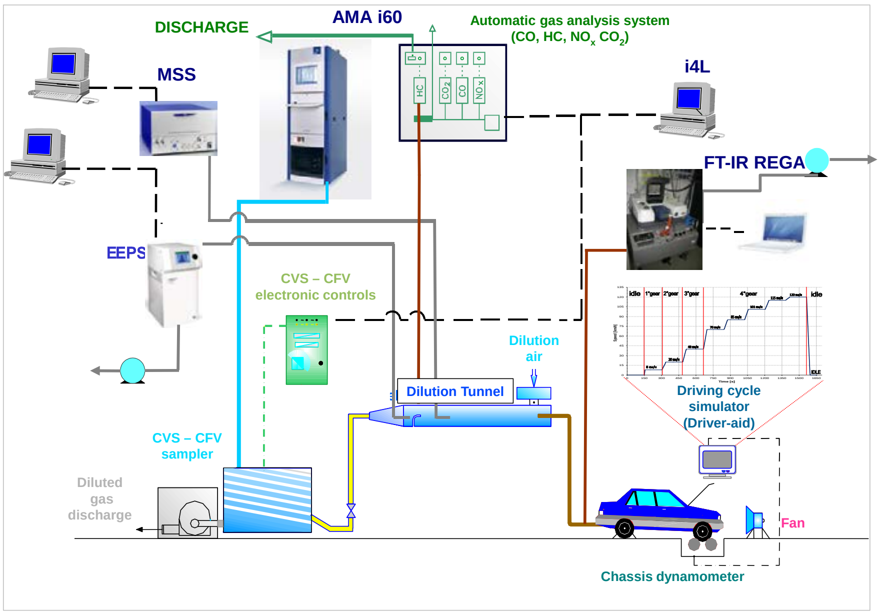

Fig.1 LEA sampling scheme

The gas analyzers have been calibrated (zero and span checks) before each test with certified gas cylinders.
Casadei and Maggioni (2016) developed the ad-hoc driving cycle referred to as Enspirit Driving Cycle (EDC), reported in Fig. 2, which was followed in every test. To develop the EDC an investigation of legislation testing procedures and of typical operating procedures about locomotive emission testing was conducted. Subsequently the EDC was created to find the best way to simulate the locomotive diesel notch-by-notch engine behavior, but using a diesel passenger car: eight phases from idle to the maximum speed (120 km/h) with the same duration for each steady state and transient. The speed and the duration of each steady state and transient through notches and the gear's changes were empirically determined, modified and verified in order to obtain for both testing vehicles rpm, exhaust flow rates and power values progressively growing correspondingly to the progression of notches and speeds. The EDC thus obtained was considered well representative of locomotive engine emissions testing and behavior and it is represented in Fig. 2.

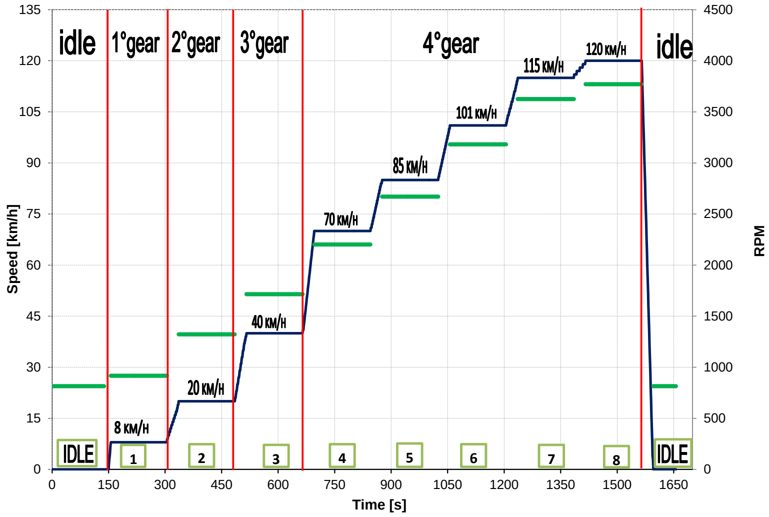

Fig. 2 ENSPIRIT Driving Cycle (EDC). Numbers and "IDLE" into the green square stand for notch number. The cars' speed and gears at each notch are showed too. Green lines represent engine rotation per minute (RPM) at each notch

The ENSPIRIT® pre-prototype was the integration of different subsystems through which the exhaust flow passed and each of whom was designed to reduce a certain pollutant concentration. A short description of the pre-prototype, compatible with its protection by patent is here reported. With the aim to reduce part of PM and NO_x emissions, a couple of turboscrubbers were employed: the first one after a flowmeter that was used to detect the exhaust flow rate and connected to the car's tailpipe, the second one at the bottom of the flow line of ENSPIRIT®, before the link to the laboratory CVS system. Patented cyclones were also used to collect further PM and an ozone generator was integrated into the system to increase the NO_x reduction rate to N_2 and H_2O. There was also a complex water mains supplied system, used to feed turboscrubbers and to assist with cooling and heating several components (e.g. a heat exchanger which required 60 l/min water to remove 40kW). The ozone generator required to be supplied by pressurized dry air having a dew point of minimum – 60°C and an inlet flow rate of 6.2 Nm^3/h; a suitable air drier was installed upstream for this purpose.

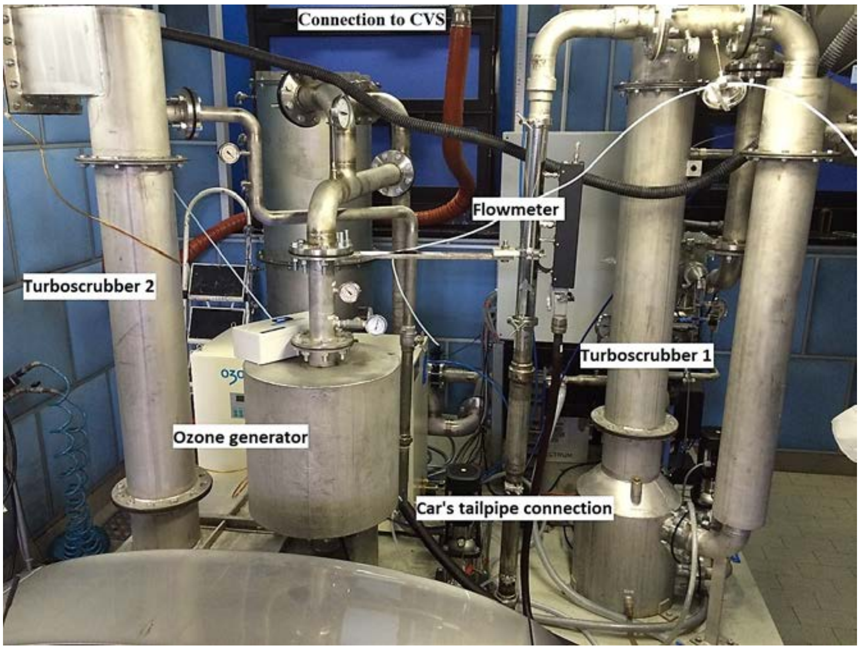

Fig. 3 ENSPIRIT® pre-prototype front side view

All instantaneous emissions data have been related to the average volumetric flow rate values [Nm^3/h] for each notch whose standard deviation determined on numerous tests was found to be very low. The volumetric flow rate through the ENSPIRIT® system was very stable at each notch and therefore the average data obtained at each notch have been used to calculate the emissions data and considered as reference values. Any transient was therefore not included in the emission calculation.

3. Results and discussion

3.1. Pre-prototype setup optimization and Testing phase results

All VW Golf 1.9 TDI emission values examined in this study, i.e. NO_x, PM by particle number and soot fraction, were first measured without employing the ENSPIRIT® pre-prototype and have been checked to be repeatable at each notch over three consecutive tests, in order to get a good baseline test, which will be hereafter referred to as *without ENSPIRIT®* tests.
Excluding any transient conditions, it was also checked the exhaust flow through the pre-prototype, in normal cubic meter per hour (Nm^3/h), to be stable over each notch. Since the volumetric flow rate through the ENSPIRIT® pre-prototype seemed to be very stable, it was processed as an average value for each notch and afterward used as a reference flow value for all emission data calculations.
The ENSPIRIT® pre-prototype was linked to the tailpipe of the first testing car to evaluate the preliminary ENSPIRIT® abatement skills. As a poor repeatability was attained for both NO_x and PMsoot, it was clear that some adjustments were needed at this first step. Welding every connection point of the connecting tubes led to a significant improvement in terms of repeatability, zeroing every emission loss. All emission values reductions were still far from the ENSPIRIT project's final target and the ENSPIRIT® abatement capabilities needed to be more effective. This was achieved by changing the pre-prototype set-up in terms of water circulation, increasing O_3 generator flow, shifting its inlet from turboscrubber 2 to 1 and modifying the O_3 introduction.
Then many tests were carried out until three repeatable tests were obtained (test 41, 42 and 43) in order to get a first response about ENSPIRIT® emissions abatement capability. These results are shown in Fig. 4: every examined pollutant species has been found to be lower than the baseline values.

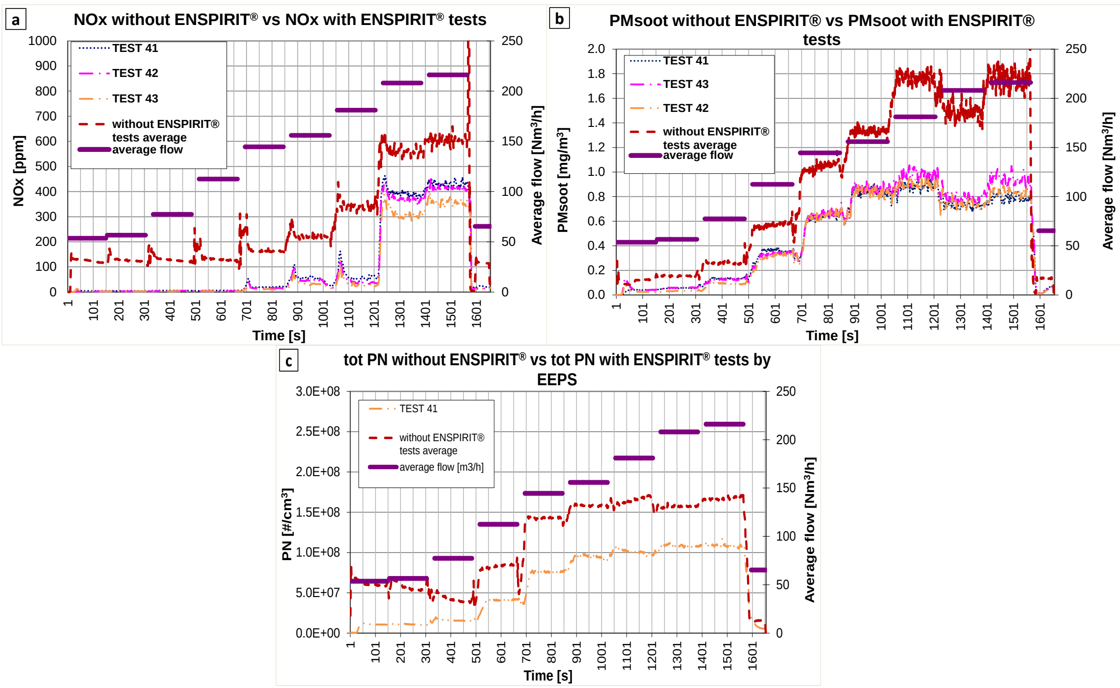

Fig. 4 Comparison of NOx (a), PMsoot (b) and PN fraction (c) with and without linking the ENSPIRIT® pre-prototype

By looking at all PN collected data a reduction of the total PN between 30 and 80% with the ENSPIRIT® activation can be observe, with the highest percentage reduction at the lowest notches. Regarding NO_x emission, both NO and NO_2 species have been also detected separately by FT-IR. NO emission values with the ENSPIRIT® connected compared to NO ones detected without the ENSPIRIT® were significantly reduced at every notch. Without the ENSPIRIT® connected NO emissions were significantly higher than NO_2 ones. NO_2 emission values with the ENSPIRIT® connected were lower (close to zero) in the idle phase and in the first part of EDC, then a peak was observed in the middle of the EDC becoming really high in the last notches, even ten times higher than the average baseline values detected without ENSPIRIT. This behavior can be ostensibly

related to the effectiveness of the pre-prototype in oxidizing NO to NO_2 by using O_3.
NO_x by CLD and PMsoot by MSS emission values resulted to be the most compatible species (within the available measured ones) with the limits set up by the regulations on diesel locomotive emissions about NO_x and PM2.5. They were also the easiest 1 Hz measurements to be integrated on the EDC steady states to obtain NO_x and PM g/bhp-hr as reported in Tier 4 standards. All of this led us to choose them as the most representative measurements to be considered to assess the effectiveness of the ENSPIRIT® pre-prototype in reducing NO_x and PM2.5 emissions, compared with the Project final goals. Instead of real time emission values, they will be hereafter reported as a function of EDC steady states values, referring to the locomotive notches. The data have been processed by Student's t-test to determine if the two sets of data (with and without ENSPIRIT® running) were statistically significantly different from each other. The degrees of freedom have been calculated by the 95% confidence interval. Although transient conditions have always been excluded, the ENSPIRIT® NO_x and PM abatement capability was investigated by considering either the emissions steady-state phases (excluding the initial decreasing part of the peaks after transitories, as shown in modal emissions in Fig. 4) or the EDC whole notch in the determination of the emissions average values. As no significant differences have been found, the EDC whole notches have then been taken into account for every calculation.

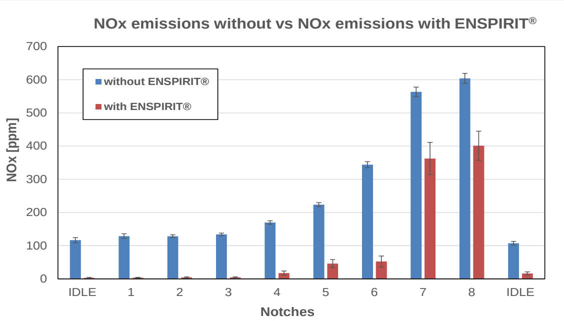

Fig. 5 NO_x emission reduction with and without ENSPIRIT®

Table 1. NO_x percentage reduction at each notch.

Efficiency of NO_x emission reduction [%]	
IDLE	97
1	97
2	96
3	97
4	99
5	80
6	85
7	36
8	34
IDLE	85

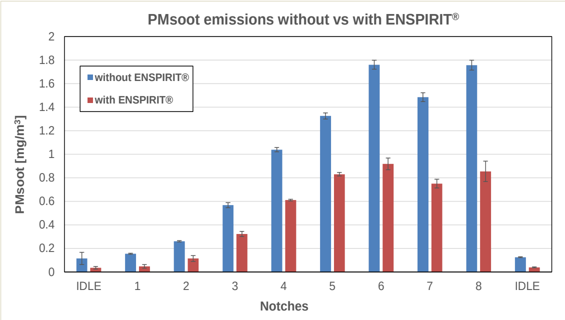

Fig. 6 PMsoot emission reduction with and without ENSPIRIT®

Table 2. PMsoot percentage reduction at each notch.

Efficiency of PMsoot emission reduction [%]	
IDLE	69
1	69
2	56
3	43
4	41
5	37
6	48
7	49
8	51
IDLE	69

As Fig. 5 - Table 1 and Fig. 6 - Table 2 show, the ENSPIRIT® NO_x and PMsoot abatement skills have been found to be more effective in the first notches, on average. In the end, every percentage difference detected for all notches (except the initial idle phase for PMsoot emission) were verified to be statistically significant by the application of a second level statistical analysis through the Student's t-test.
It was also chosen to investigate the particulate number distribution notch-by-notch. As good repeatability was obtained for both setups, particle-size distribution curves for one test before (test 20) and one test after connecting ENSPIRIT® pre-prototype (test 41) have been reported in Appendix A. Although the reduction of nuclei mode particles looks higher than the one for the accumulation mode for all notches, the ENSPIRIT® pre-prototype particle abatement capability was higher in the first notches, reaching 90% efficiency, decreasing to 30% efficiency for the last notches.
Approximately, over all notches for NO_x and PMsoot raw data average final reductions of 64% and 47% were reached, respectively. In order to compare the emission results with the ones reported by legislation on Tier 4, the final emission reduction values have been converted to grams per horsepower per hour, as showed in Table 3.

Table 3. NO_x [g/bhp-hr] and PMsoot [g/bhp-hr] VW Golf 1.9 TDI removal efficiencies. Final percentage removal efficiencies are marked by a red rectangle.

		NOx													
		Tests **without** ENSPIRIT							Tests **with** ENSPIRIT						
		Tier 4	Tier 4 weighting						Tier 4	Tier 4 weighting					
Notch	Duration, s	g/bhp-hr	Line-haul		Passenger		Switch		g/bhp-hr	Line-haul		Passenger		Switch	
Idle	150	**18.309**	50.5%	9.246	53.6%	9.814	59.8%	10.949	**0.731**	50.5%	0.369	53.6%	0.392	59.8%	0.437
1	150	**14.782**	6.5%	0.961	7.0%	1.035	12.4%	1.833	**0.576**	6.5%	0.037	7.0%	0.040	12.4%	0.071
2	150	**7.124**	6.5%	0.463	5.1%	0.363	12.3%	0.876	**0.363**	6.5%	0.024	5.1%	0.019	12.3%	0.045
3	150	**4.109**	5.2%	0.214	5.7%	0.234	5.8%	0.238	**0.198**	5.2%	0.010	5.7%	0.011	5.8%	0.011
4	150	**3.945**	4.4%	0.174	4.7%	0.185	3.6%	0.142	**0.572**	4.4%	0.025	4.7%	0.027	3.6%	0.021
5	150	**3.044**	3.8%	0.116	4.0%	0.122	3.6%	0.110	**0.901**	3.8%	0.034	4.0%	0.036	3.6%	0.032
6	150	**3.369**	3.9%	0.131	2.9%	0.098	1.5%	0.051	**0.718**	3.9%	0.028	2.9%	0.021	1.5%	0.011
7	150	**4.332**	3.0%	0.130	1.4%	0.061	0.2%	0.009	**3.894**	3.0%	0.117	1.4%	0.055	0.2%	0.008
8	150	**4.287**	16.2%	0.695	15.6%	0.669	0.8%	0.034	**3.918**	16.2%	0.635	15.6%	0.611	0.8%	0.031
Idle	60	**19.165**							**4.808**						
			Tier 4 limit is 1.3>	12.129		12.5804		14.2416		Tier 4 limit is 1.3>	1.279		1.21148		0.66777
										removal efficiences>	**89%**		**90%**		**95%**

		Soot													
		Tests **without** ENSPIRIT							Tests **with** ENSPIRIT						
		Tier 4	Tier 4 weighting						Tier 4	Tier 4 weighting					
Notch	Duration, s	g/bhp-hr	Line-haul		Passenger		Switch		g/bhp-hr	Line-haul		Passenger		Switch	
Idle	150	**0.012**	50.5%	0.006	53.6%	0.007	59.8%	0.007	**0.004**	50.5%	0.002	53.6%	0.002	59.8%	0.003
1	150	**0.0121**	6.5%	0.0008	7.0%	0.0008	12.4%	0.0015	**0.0040**	6.5%	0.0003	7.0%	0.0003	12.4%	0.0005
2	150	**0.0099**	6.5%	0.0006	5.1%	0.0005	12.3%	0.0012	**0.0045**	6.5%	0.0003	5.1%	0.0002	12.3%	0.0006
3	150	**0.0119**	5.2%	0.0006	5.7%	0.0007	5.8%	0.0007	**0.0070**	5.2%	0.0004	5.7%	0.0004	5.8%	0.0004
4	150	**0.0165**	4.4%	0.0007	4.7%	0.0008	3.6%	0.0006	**0.0099**	4.4%	0.0004	4.7%	0.0005	3.6%	0.0004
5	150	**0.0124**	3.8%	0.0005	4.0%	0.0005	3.6%	0.0004	**0.0080**	3.8%	0.0003	4.0%	0.0003	3.6%	0.0003
6	150	**0.0118**	3.9%	0.0005	2.9%	0.0003	1.5%	0.0002	**0.0062**	3.9%	0.0002	2.9%	0.0002	1.5%	0.0001
7	150	**0.0078**	3.0%	0.0002	1.4%	0.0001	0.2%	0.0000	**0.0040**	3.0%	0.0001	1.4%	0.0001	0.2%	0.0000
8	150	**0.0085**	16.2%	0.0014	15.6%	0.0013	0.8%	0.0001	**0.0041**	16.2%	0.0007	15.6%	0.0006	0.8%	0.0000
Idle	60	**0.0153**							**0.0057**						
			Tier 4 limit is 0.03>	0.012		0.0117		0.0121		Tier 4 limit is 0.03>	0.005		0.00483		0.0048
										removal efficiences>	**58%**		**59%**		**61%**

First mg/m^3 emission values were converted to grams per cubic meter values. The estimated engine's horsepower (bhp) was calculated using the power detected by chassis dynamometer (kiloWatt - kW) adding the losses that normally occur from engine to chassis dynamometer, which were previously evaluated being around 30%. Idle horsepower was chosen to be calculated as 1% out of the max value detected in correspondence of notch eight. The power kW values were converted to bhp ones and then divided by the time to obtain horsepower-hour values (bhp-hr) which were then taken into account for each notch as reference engine powers. The average volumetric gas flow [Nm^3/hr] was calculated for each notch through the CO_2 dilution ratio. NO_x and PMsoot raw values, as directly measured by the instruments, were converted to mg/Nm^3 values that were then converted to grams and finally divided by bhp-hr values (bold grey numbers in Table 3 and in Table 6) in order to be compared with the limits reported in Tier 4 Locomotive Emission Standards Regulatory Support Document, publisheb by EPA (1998). These values have been inserted into the Table 3, which reports the NO_x values (above) and PMsoot values (below). Three types of locomotives are currently referred as standard trains as the Document shows: Line-haul, Passenger and Switch. Depending on how much time each locomotive typology was detected to be used in a certain state (or notch) during its working life, a percentage emission weighting factor was estimated by EPA (1998) for each notch that is reported in Table 3 and in Table 6. Because the last idle notch is not considered in Tier 4, it has not been taken into account in Table 3 and in Table 6.

According to these percentages NO_x and PMsoot emission values also collected during the Validation phase have been processed as weighted averages, and they are reported in the following chapter. By summing the weighted averages for each locomotive typology the final emission value can be compared with the Tier 4 limit in order to establish the effectiveness of ENSPIRIT® pre-prototype in reducing NO_x and PMsoot emissions below the standard limit.

Concerning NO_x and PM final emission data expressed as g/bhp-hr as average values over the EDC cycle, in the pre-prototype Testing phase a reduction of 90% and 60% were reached, respectively.

3.2. *Validation phase results*

After having found the best ENSPIRIT® setup during the Testing phase, an Alfa Romeo 159 1.9 JTD, previously deprived of all after treatment devices (DOC, DPF, EGR), has been chosen and driven on the ENSPIRIT Driving Cycle (EDC). The same EN590-compliant diesel fuel that fed VW Golf 1.9 TDI during the Testing phase has been used as well for the Validation phase.

During the Validation phase the two emission species have been investigated, which were previously identified as the most suitable ones to demonstrate the ENSPIRIT® effectiveness: NO_x diluted emissions [ppm] and the particulate matter soot fraction in the exhaust [mg/m^3].

A number of tests suitable to obtain good repeatability results have been carried out without and with the ENSPIRIT® pre-prototype (the latter reached in tests 53, 54, 55): the ENSPIRIT® effectiveness to reduce PM and NO_x emissions values has been shown by comparing NO_x and PM2.5 values obtained during the tests without and with ENSPIRIT®.

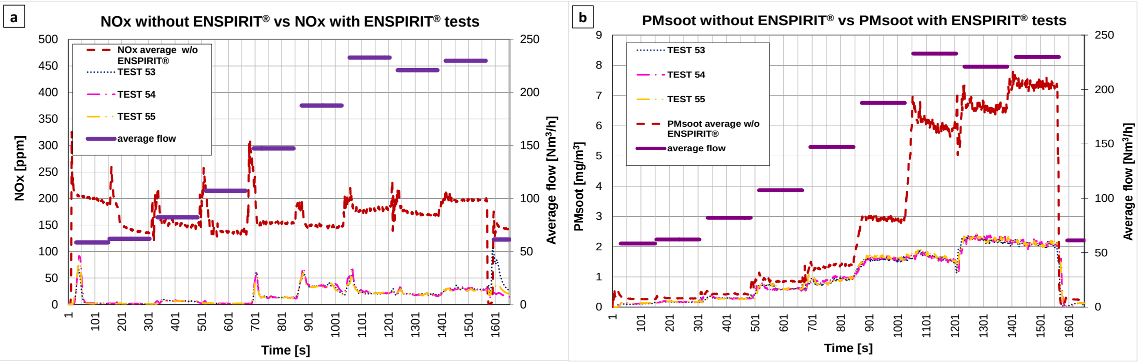

Fig. 7 Comparison of NOx (a), PMsoot (b) with and without linking the ENSPIRIT® pre-prototype. w/o ENSPIRIT stands for without ENSPIRIT® connected.

In the same way as in the previous Testing phase, EDC single notches have been used to calculate the average emissions for each notch as Fig. 7 shows.
The same statistical test has been applied in the Validation phase in order to detect whether the differences between the two sets of data were statistically significantly different from each other, whose results are reported in Fig. 8 and in Fig. 9.

Table 4. NO_x percentage reduction at each notch.

Efficiency of NO_x emission reduction [%]	
IDLE	92
1	99
2	95
3	99
4	88
5	80
6	85
7	90
8	80
IDLE	80

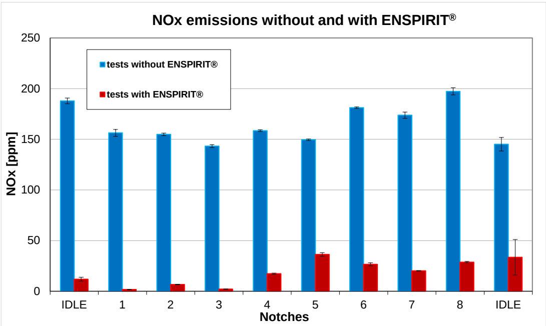

Fig. 8 NO_X emission reduction with and without ENSPIRIT®

Table 5. PMsoot percentage reduction at each notch.

Efficiency of PMsoot emission reduction [%]	
IDLE	65
1	42
2	33
3	27
4	35
5	45
6	73
7	66
8	71
IDLE	64

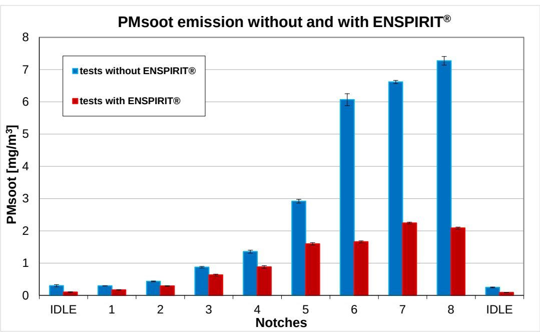

Fig. 9 NO_X emission reduction with and without ENSPIRIT®

As Table 4 and Table 5 show, the ENSPIRIT NO_x abatement capability has been found to be higher in the first notches whereas the PMsoot ones in the last notches. All the percentage differences detected for each notch were found to be statistically significant by Student's t test.
These ppm and mg/m^3 emission reduction values were correlated for every single notch as g/bhp-hr engine's horsepower, following the same procedure as the Testing phase.

Table 6. NO_x [g/bhp-hr] and PMsoot [g/bhp-hr] Alfa Romeo 159 1.9 JTD removal efficiencies. Final percentage removal efficiency are marked by a red rectangle.

		NOx													
		Tests **without** ENSPIRIT							Tests **with** ENSPIRIT						
		Tier 4	Tier 4 weighting						Tier 4	Tier 4 weighting					
Notch	Duration, s	g/bhp-hr	Line-haul		Passenger		Switch		g/bhp-hr	Line-haul		Passenger		Switch	
Idle	150	**27.106**	50.5%	13.689	53.6%	14.529	59.8%	16.209	**3.147**	50.5%	1.589	53.6%	1.687	59.8%	1.882
1	150	**16.167**	6.5%	1.051	7.0%	1.132	12.4%	2.005	**0.302**	6.5%	0.020	7.0%	0.021	12.4%	0.037
2	150	**7.833**	6.5%	0.509	5.1%	0.399	12.3%	0.963	**0.529**	6.5%	0.034	5.1%	0.027	12.3%	0.065
3	150	**4.009**	5.2%	0.208	5.7%	0.228	5.8%	0.232	**0.091**	5.2%	0.005	5.7%	0.005	5.8%	0.005
4	150	**2.377**	4.4%	0.105	4.7%	0.112	3.6%	0.086	**0.382**	4.4%	0.017	4.7%	0.018	3.6%	0.014
5	150	**1.949**	3.8%	0.074	4.0%	0.078	3.6%	0.070	**0.666**	3.8%	0.025	4.0%	0.027	3.6%	0.024
6	150	**2.201**	3.9%	0.086	2.9%	0.064	1.5%	0.033	**0.418**	3.9%	0.016	2.9%	0.012	1.5%	0.006
7	150	**1.331**	3.0%	0.040	1.4%	0.019	0.2%	0.003	**0.221**	3.0%	0.007	1.4%	0.003	0.2%	0.000
8	150	**1.465**	16.2%	0.237	15.6%	0.229	0.8%	0.012	**0.298**	16.2%	0.048	15.6%	0.046	0.8%	0.002
Idle	60	**21.192**							**9.280**						
			Tier 4 limit is 1.3>	15.999		16.7891		19.6132		Tier 4 limit is 1.3>	1.761		1.8465		2.0367
										removal efficiences>	**89%**		**89%**		**90%**

		Soot													
		Tests **without** ENSPIRIT							Tests **with** ENSPIRIT						
		Tier 4	Tier 4 weighting						Tier 4	Tier 4 weighting					
Notch	Duration, s	g/bhp-hr	Line-haul		Passenger		Switch		g/bhp-hr	Line-haul		Passenger		Switch	
Idle	150	**0.0299**	50.5%	0.0151	53.6%	0.0160	59.8%	0.0179	**0.0136**	50.5%	0.0068	53.6%	0.0073	59.8%	0.0081
1	150	**0.0211**	6.5%	0.0014	7.0%	0.0015	12.4%	0.0026	**0.0148**	6.5%	0.0010	7.0%	0.0010	12.4%	0.0018
2	150	**0.0151**	6.5%	0.0010	5.1%	0.0008	12.3%	0.0019	**0.0115**	6.5%	0.0007	5.1%	0.0006	12.3%	0.0014
3	150	**0.0168**	5.2%	0.0009	5.7%	0.0010	5.8%	0.0010	**0.0132**	5.2%	0.0007	5.7%	0.0008	5.8%	0.0008
4	150	**0.0140**	4.4%	0.0006	4.7%	0.0007	3.6%	0.0005	**0.0096**	4.4%	0.0004	4.7%	0.0004	3.6%	0.0003
5	150	**0.0260**	3.8%	0.0010	4.0%	0.0010	3.6%	0.0009	**0.0144**	3.8%	0.0005	4.0%	0.0006	3.6%	0.0005
6	150	**0.0505**	3.9%	0.0020	2.9%	0.0015	1.5%	0.0008	**0.0128**	3.9%	0.0005	2.9%	0.0004	1.5%	0.0002
7	150	**0.0347**	3.0%	0.0010	1.4%	0.0005	0.2%	0.0001	**0.0121**	3.0%	0.0004	1.4%	0.0002	0.2%	0.0000
8	150	**0.0370**	16.2%	0.0060	15.6%	0.0058	0.8%	0.0003	**0.0106**	16.2%	0.0017	15.6%	0.0017	0.8%	0.0001
Idle	60	**0.0250**							**0.0121**						
			Tier 4 limit is 0.03>	0.029		0.02863		0.02588		Tier 4 limit is 0.03>	0.013		0.01287		0.01329
										removal efficiences>	**56%**		**55%**		**49%**

A final removal of NO_x around 90%, on average, and a final removal of PMsoot greater than 50%, on average, were reached for all parametrically simulated locomotive typologies (Line-haul, Passenger and Switch).

4. Conclusion

In this experimental work it was showed that significant NO_x and PM emission reductions are achievable by using the ENSPIRIT® pre-prototype system which is based on the use of water and ozone to reduce PM and NO_x emissions from diesel combustion engine. Final NO_x and PMsoot reductions of 90% and 60% were reached in the Testing phase, respectively, and final NO_x and PMsoot reductions of 90% and 50% were reached in the Validation phase.

As showed by EEPS results, on average the most relevant particles number emission reduction occurred in the first notches, decreasing then in last ones. A remarkable particle reduction was reached especially for nuclei mode mainly in the first notches, and partially for accumulation mode.

Since the work carried out at this phase of the ENSPIRIT project was still within a research and development step, other challenges still need to be faced, e.g. the ENSPIRIT® system sustainability in terms of energy and water consumption when scaled up for a locomotive suitable use. Furthermore, since ENSPIRIT® particle reduction capability seems more efficient for smallest particles, this effectiveness will have to be confirmed and possibly improved if an upscale will be developed, targeting real locomotive diesel engines.

Despite these very promising results of the new diesel exhaust abatement methodology here tested and validated, scaling up the ENSPIRIT® prototype to be fitted for locomotive engines will be an essential step to assess its real-world NO_x and PM2.5 abatement capabilities.

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Appendix A.

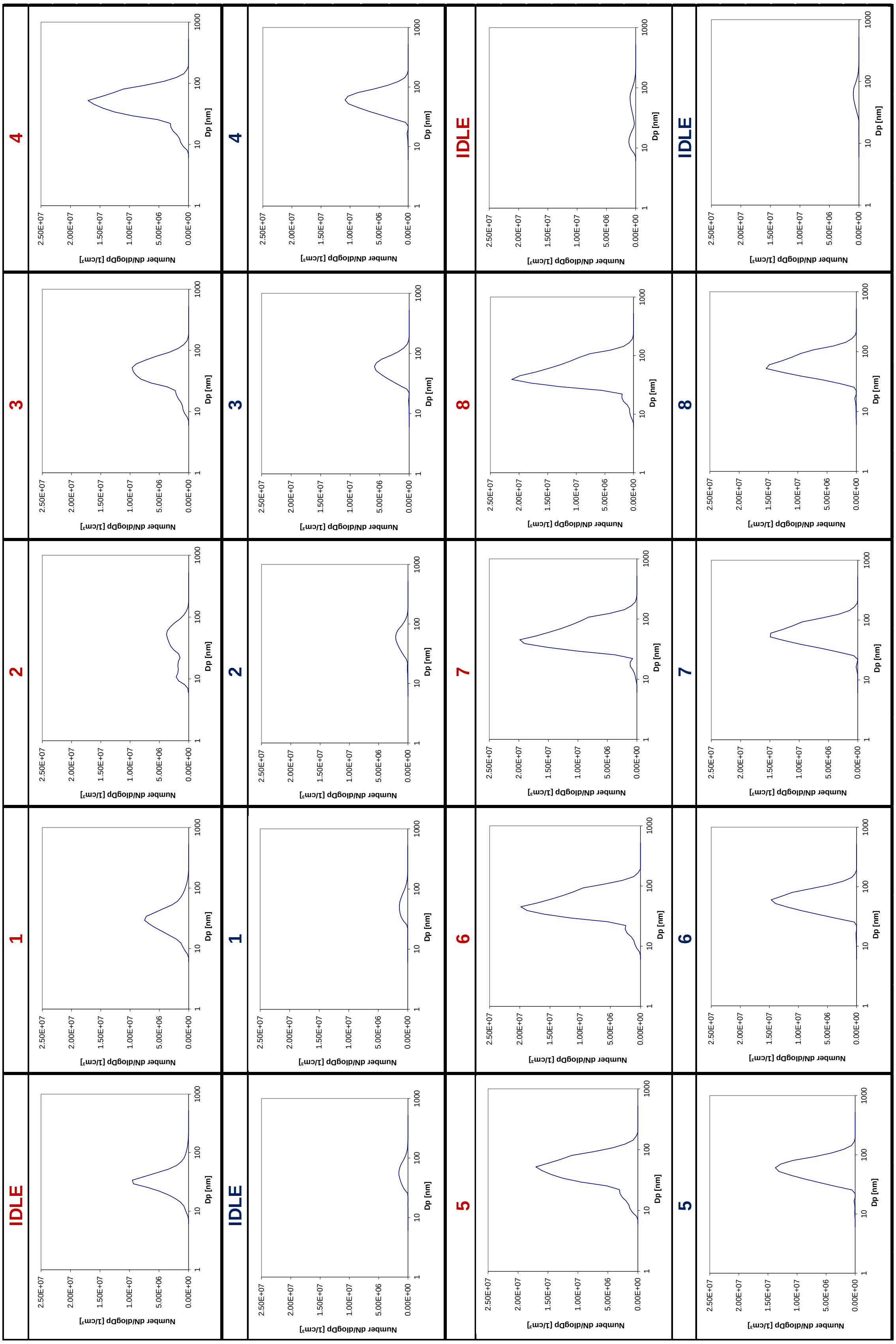

Figure 1 A. particle-size distribution curves notch-by-notch detected by EEPS. The charts with the red title refer to tests without ENSPIRIT®, the ones with the blue title refer to tests with ENSPIRIT®.