Potential for Reduction in NRMM Real-World Emissions

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Abstract. Pollutant emission regulations for Non-Road Mobile Machinery (NRMM) is currently under consideration, both in the European Union (EU) and the United States (US). In Europe a Stage V review report is expected from the European Commission by December 2025 and in the US, the California Air Resource Board (CARB) has released their Tier 5 proposal in late 2024. It is expected that there will be further focus on covering a wide variety of operation conditions in actual use cases, including continuous low load scenarios.
The objective of the work presented in this paper is to demonstrate that upcoming, more stringent emission regulations can be met with standard engine and emission control technology. A 4-liter class displacement engine with ~ 105 kW rated power and cooled EGR was selected for the project. The engine´s airpath was modified in a way that the EGR cooler could be bypassed, and the fresh air could be directed over the EGR cooler to heat up the intake air with the aim to elevate the exhaust gas temperature under low load and idle conditions. Three different emission control systems are investigated: an enhanced stage V system with single SCR, a system with dual-SCR and a system with an Exhaust Gas Heater (EGH). The system was tested on NRMM-specific type approval test cycles such as the non-road transient cycle (NRTC), the Ramped-Mode-Cylce (RMC) and the low-load cycle (LLC), as well as on various in-use cycles (bulldozer, wheel loader, forklift and excavator).
The test results show all 3 variants are within CARB Tier 5 and Euro 7 limits on NRTC. The Dual-SCR configuration and the system with the EGH are capable to meet the low-load-cycle limit while the NOx result with the Enhanced Stage V configuration is just above the Tier 5final legal NOx limit. Furthermore, consistent low emissions are observed over the range of in-use cycles.
An additional iteration of LLC h and the NRTC cold/hot using HVO fuel showed comparable or lower emissions than measured with EN590 fuel and hence a pathway for a CO_2 neutral powertrain concept for the NRMM sector was proven.

Keywords: NRMM, Tier 5, Emission control strategies

1 Introduction

Recent analysis in the Netherlands (Stoverinck) and Germany (C. Heidt) shows the impact of Non-Road Mobile Machinery (NRMM) on the air quality is becoming more significant. The reductions in NRMM emissions were less pronounced than those in the on-road transport sector, so the relative contribution increased. The pollutant emission regulation for NRMM is currently under consideration. In the European Union, the European Commission is expected to publish a review report on the Stage V Regulation by 31 December 2025 based on collected In-Service Monitoring data. In US, CARB already published a draft proposed Regulation Order on Tier 5 on 24 September 2024 (CARB).

1.1 CARB Tier 5 emission legislation

The CARB Tier 5 overview is shown in Table 1 and 2. For the power categories between 56 to 130 kW and 130 to 560 kW a 2-phase introduction is planned. The Tier 5 interim standard will be introduced in 2029. One of the main differences between today's Tier 4 final standard is the reduction of the Particulate Matter (PM) limit from 0.02 g/kWh to 0.005 g/kWh in the NRTC with cold/hot weighing and the RMC (Non-Road Transient Cycle, Ramped Mode Cycle). This 75 % reduction of the PM limit mandates the integration of a Diesel Particulate Filter (DPF) into the emission control system. Another difference is the reduction of the NOx emission limit to 0.22 g/kWh in the interim stage and to 0.04 g/kWh in the final stage. The Tier 5 final standard will be introduced in 2034+ for the smaller power category and in 2033+ for the power category between 130 and 560 kW. Alongside the reduction of the emission standards in the NRTC and RMC a Low-Load Cycle (LLC) will be introduced in the final stage and the greenhouse gas emissions (N_2O, CO_2 and CH_4) will be limited. Furthermore, idle limits depending on engine power category will be introduced (Table 3).

Table 1: Overview CARB Tier 5 emission and Greenhouse-Gas limits

Duty Cycle	Power Category	Regulation Standard	Pollutant Regulation		GHG Regulation		
			NO_x Limit [g/kWh]	PM Limit [g/kWh]	N_2O Limit [g/kWh]	CO_2 Limit [g/kWh]	CH_4 Limit [g/kWh]
NRTC c/h & RMC	19≤kW≤56 (25≤hp≤75)	Tier 5 **interim**	3.7	0.015			
		Tier 5 final	2.5	0.008	0.15	962.5	0.130
	56≤kW≤560 (75≤hp≤750)	Tier 5 **interim**	0.22	0.005			
		Tier 5 final	0.04		0.15	773.4 – 724.2*	0.130
LLC	56≤kW≤560 (75≤hp≤750)	Tier 5 final	0.06	0.005			

Table 2: CARB Tier 5 final idle standards

Duty Cycle	Power Category	Emission Standard	NO_x Limit [g/h]	NO_x Limit range [g/h]
Idle Standard	19≤kW≤56 (25≤hp≤75)	Tier 5 final	0.536 * P	10 - 30
	56≤kW≤130 (75≤hp≤175)	Tier 5 final	5 or 0.0769*P Whichever is greater	5 - 10
	130≤kW≤560 (175≤hp≤750)	Tier 5 final	5 or 0.0282*P Whichever is greater	10 – 15.8

Table 3: Overview CARB Tier 5 interim & final introduction dates

Option	Power Category	Year					
		2029	2030	2031	2032	2033	2034
Option 1 - 3	< 130 kW	Tier 4 final		Tier 5 interim			Tier 5 final
	130 ≤ kW ≤ 560	Tier 5 interim				Tier 5 final	
	>560 kW	Tier 4 final	Tier 5 interim				Tier 5 final
Option 4	< 130 kW	Tier 4 final			Tier 5 final		
	130 ≤ kW ≤ 560	Tier 4 final		Tier 5 Final			
	>560 kW	Tier 4 final			Tier 5 Final		

To ensure that NOx and PM emissions from off-road vehicles align with laboratory standards during real-world operation, CARB plans to monitor the in-use performance of emission control systems. CARB proposes evaluating NOx emissions using sensor data and the 3-bin evaluation method. This time-window based evaluation is like the approach proposed for the on-road sector by EPA, but the windows are categorized into three bins: idle, low load, and high load. The NOx limits for each bin are based on the NRTC/RMC limit (high bin), LLC limit (low bin), and idle limit (idle bin), with a conformity factor of 1.5 plus a NOx sensor margin.
Some simulation- and engine dyno based investigations dealing with possible technology configurations on the engine and emission control side to meet the upcoming Tier 5 standards have been performed already (Demuynck), (G. Neely), (Fnu).

1.2 Euro 7 legislation

The emission limits of the upcoming Heavy-duty Euro 7 regulation are considered as another scenario for a potential step beyond Stage V regulation for the NRMM sector in Europe. Hence the test results of this paper will be compared to the respective Euro 7 limit in addition to the CARB Tier 5f limits. In Table 4 the limit values for HD Euro 7 are listed.

1.3 Case study - in-use emissions of NRMM

The authors of the Association for Emission Control and Climate (AECC) previously analysed Real-World NOx emissions of a variety of Stage V machines with the Dutch Organization for Applied Scientific Research (TNO) (Vermeulen). It was observed that engine load patterns vary between machines, even when they are of the same type. In general, the average engine load is relatively low or can have intermittent periods of working and stand-by periods. A variety in real world average emissions performance was observed. Overall, a discrepancy between engine-certified and application-related real-world NOx emission has been identified. It is expected this will be handled in future NRMM emission legislation to further improve local air quality. This is the basis for the work presented here.

Table 4: Heavy-duty Euro 7 pollutant emission limits

Pollutant Emissions	WHTC	RDE (ISC)
	Euro 7 WHTC c/h combined (14% / 86%)	Euro 7 ISC c/h combined (14% / 86%)
	per kWh	per kWh
NOx in mg	200	260
PN_{10} in #	6x10^11	$9*10^{11}$
NH_3 in mg	60	85
N_2O in mg	200	260
CH_4 in mg	500	650
PM in mg	8	-
CO in mg	1500	1950
NMOG in mg	80	105

2 Demonstrator system

2.1 Engine

As demonstrator engine, the Deutz TCD 3.6 engine, a dedicated NRMM diesel engine with a maximum power output of 105 kW was used. The specifications of the engine and a picture are shown in Table 5.

Table 5: Demonstrator engine specification

Engine specification		
Series	TCD 3.6	
Number of cylinders	4	#
Bore	98	mm
Stroke	120	mm
Displacement	3.6	ltr
Max. speed	2300	rpm
Max power output	105	kw @ 2300 rpm
Max. torque	550	Nm

The TCD 3.6 engine is certified to the European Stage V and Tier 4f emission standards. This engine features a two-valve design, a cam-in-block configuration, and a cooled high-pressure Exhaust Gas Recirculation (EGR) system, which is representative for NRMM in this power class. In addition, the engine is equipped with an intake throttle to control EGR and intake air flow. To meet the stringent Tier 5f requirements for heat-up and keep-warm strategies, the air path was adapted by incorporating an uncooled EGR system. Specifically, an EGR cooler bypass, as well as a charge air cooling bypass, allowing controlled fresh air flow over the EGR cooler (Figure 1). The adapted airpath strategy was mainly applied in and around the idle point to elevate the exhaust gas temperature and ensure a sufficiently high temperature in the emission control system during prolonged low load and idling periods. To control the air path, which deviates from the standard production architecture, a rapid prototype ECU, the AVL RPEMS, was used.

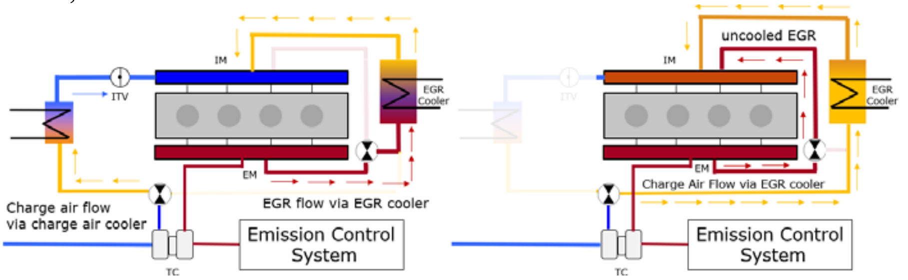

Figure 1:Standard (left) and alternative (right) airpath concept

The setup on the AVL testbed showing the engine with the alternative airpath and the modular emission control system is depicted in Figure 2.

Figure 2: Testbed setup on AVL testbed

2.2 Emission control systems

NRMM encompasses a wide range of applications with diverse requirements and packaging constraints. In most applications, packaging is the primary challenge, while fuel consumption is a secondary concern. Fuel efficiency becomes the primary focus only in particular scenarios where packaging constraints are less critical. In the present study a modular cigar-type emission control system was manufactured allowing to test three different configurations, see Figure 3. and to explore different solutions how to meet the upcoming, stringent emission regulations. Starting from the base Stage V architecture (Enhanced Stage V concept/Variant 1), including an Fe/Cu Zeolite SCR to minimize the N_2O emissions, an additional light-off SCR (LO-SCR) + mixer was introduced (Dual-SCR/Variant 2). For the LO-SCR, the Ti/V SCR technology was selected due to its resistance to sulfur poisoning and due to its low N_2O formation in the temperature range below 450 °C. Additionally, an Exhaust Gas heater (EGH) was welded into the system after the filter (Enhanced Stage V+ EGH/Variant 3). The heater was present in the system during the entire testing campaign, while it was only activated in the respective test cycles. The heater power was added to the inner engine torque considering an electric efficiency of 90 %.

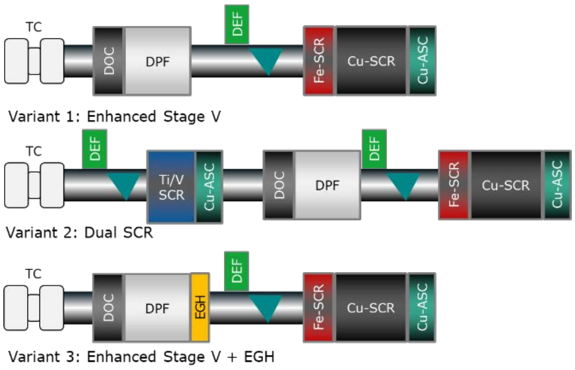

Figure 3: Schematics of the emission control systems in scope of the study

In Figure 4 the modular emission control system as manufactured in-house at AVL using the canning provided by the OEM is depicted. The first SCR stage is attached via a V-clamp and the Exhaust Gas Heater is welded to the DPF canning and the following AdBlue© mixer section using conical steel parts. All catalysts were in hydrothermal aged condition and the ageing procedure was conducted in the electric oven.

Figure 4: Modular emission control system

2.3 AdBlue© dosing system

To realize the Dual-SCR configuration 2 separate AdBlue© dosing system with separate supply modules and AdBlue© tanks were installed on the testbed. The control and interaction of the separate system was realized in the AVL RPEMS environment. The AdBlue© dosing system was supplied by the OEM and relies on airless dosing technology using an operating pressure of 9 bar.

2.4 Test cycles

NRTC. In line with the specification in the regulation the NRTC cycle was run in two phases – a cold and a hot phase interrupted by a 20-minute-long soak time. Before the cold cycle an NH_3 loading was established on the SCR catalysts(s) by a preconditioning cycle (NRTC h/h) followed by an overnight soak period with a minimum duration of 8 hours. The cold phase was weighted with 5 % according to the US EPA regulation.

Low-Load Cycle (LLC). The LLC - as proposed by CARB - was run as a cold and as hot started cycle. The cycle was either started after an NRTC Cold/hot + 20 minutes soak time (hot cycle)/overnight soak (cold cycle) or after a single phase of the NRTC cycle + 20 minutes soak time. For all operating points representing the idle condition, an engine torque corresponding to 3.5 % (i.e. 44 Nm) of the engine´s rated power (top rating) was applied.

Ramped-Mode-Cycle (RMC). The RMC was run as a hot started cycle. As preconditioning an RMC cycle + 20 minutes soak time was performed.

In-use load profiles. To investigate the performance of the Emission Control Systems out of the laboratory cycles a variety of in-use load profiles (Figure 5) representing different applications was tested. The in-use cycles were started directly after an NRTC h which served as a preconditioning cycle.

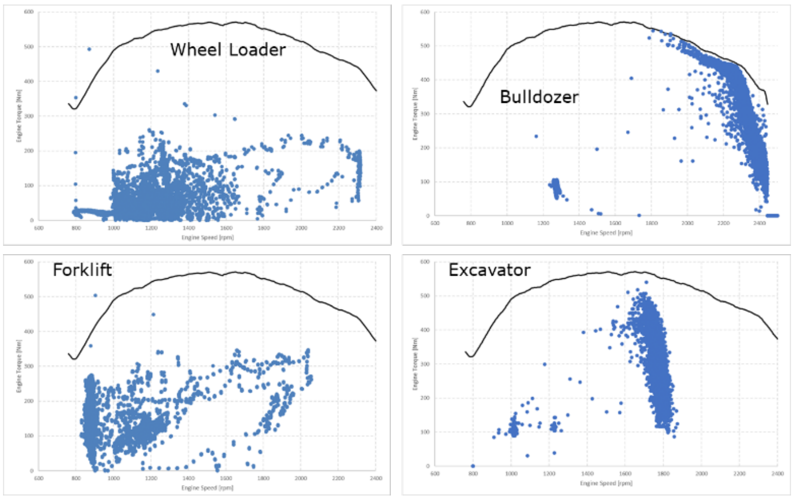

Figure 5: Engine speed + torque data of the in-use load profiles

2.5 Measurement devices

Gaseous emissions. The gaseous emissions were measured using two AVL AMA i60 devices and two AVL FTIR devices. One AMA was used to measure the engine´s raw emissions, the second AMA together with one of the FTIR devices was located at the outlet of the emission control system. The second FTIR device was used to measure the gaseous emissions at the outlet of the first SCR system. Regarding the HC emissions in this study the Total Hydrocarbons (THC) are reported whereas in the Tier 5f and Euro 7 regulation only Non-Methane Hydrocarbons (NMHC) limits are specified. As the Methane share of THC is usually low in Diesel engine exhaust the difference between NMHC and THC is in the range of 1 mg/kWh.

Particulate Number Emissions. The Particulate Number (PN) emissions were measured using two AVL Particle Counter 489 APC xApp dual. The device is capable of simultaneously measure PN10 and PN23 emissions. The particle counters were either positioned at the turbine outlet before the emission control system/after the filter, to measure the PN Filtration efficiency over the DPF or after the filter/tailpipe to detect the urea born particle formation.

Particulate Mass. The Particulate Mass emissions were measured with an AVL Smart Sampler 478 device.

2.6 Control Strategy

Engine. The demonstrator engine has several engine modes and for the testing campaign 2 of them – the heat-up mode and the normal mode - were used. The heat-up mode was active directly after cold start and aims to bring the emission control system in a suitable temperature range as fast as possible. Once the threshold temperature in the emission control system is reached (gas temperature upstream SCR > 240 °), the engine switches to the normal mode. To maintain the temperature in the ECS in the desired temperature range, the engine will switch back to the heat-up once the gas temperature upstream SCR drops below 220 °C.
During idling conditions, the alternative airpath concept was activated allowing the intake air to flow over the EGR cooler and route the EGR flow directly back to the intake manifold without flowing through the EGR cooler.

SCR system. In case of a single-SCR arrangement, a state-of-the art NH_3 storage-based algorithm was applied. For the dual-SCR configuration, the balancing of the dosing between the 2 SCR stages was conducted as described in the following:
If the substrate temperature of the main SCR is below 300 °C both SCR systems operate in NH_3 storage-based control mode. Once the threshold of 300 °C is passed the operating strategy of the first SCR system is adapted to an open loop strategy. The NH_3 to NOx ratio upstream of the first SCR is then reduced 50 %, allowing NOx to pass

through and enable NO_2-based soot oxidation on the DPF. In the second SCR system the NH_3 storage-based control algorithm is maintained continuously, independent of the conditions in the emission control system.

Exhaust gas heater. The activation and deactivation of the Exhaust Gas Heater (EGH), included in emission control system variant 3, depends on the current and the demanded exhaust gas temperature in front of the SCR system. The control strategy is based on the difference between the demanded and the actual temperature and the heating power is reduced as the actual temperature is coming closer to the target temperature (210 °C gas temperature upstream main SCR). Furthermore, a limitation based on exhaust mass flow was introduced.

3 Results

3.1 NRTC cold/hot

The Tailpipe results for all three emission control system variants and the NOx engine out emissions are summarized in Table 6. All 3 ECS variants are meeting the Tier 5f and Euro 7 legal limits. The Dual-SCR system reaches the lowest combined NOx, N_2O and PN10 results and the NH_3 slip is below 1 ppm on average for all tested variants. The PM emissions were measured in the tests with the Enhanced Stage V ECS variant and were below 1 mg/kWh in 2 iterations.

Table 6: NRTC Cold/hot results with 3 different emission control systems

ECS	Unit	Variant 1 (Enhanced Stage V)	Variant 2 (Dual-SCR)	Variant 3 (Enhanced Stage V 2.5 kW EGH)	Variant 3 (Enhanced Stage V 2.5 kW EGH)	Legal Limit Tier 5	Legal Limit Euro 7
Species		Results					
NOx EO	mg/kWh	4013	4131	4023	3995	-	
CO		6	8	2	15	5000	1500
THC		1	1	1	2	80	160
NOx combined		21	13	16	19	40	200
cold phase		404	233	308	367		
hot phase		1	2	0	1		
N2O		27	22	31	32	150	200
PM		<1				5	8
NH3	ppm	<1				10	60
PN10	#/kWh	1.96E+11	8.51E+10	2.06E+11	N/A	N/A	6E+11

NOx emissions. The main difference in terms of NOx conversion efficiency between the 3 systems can be seen in the cold phase of the NRTC (Figure 6) while in the hot phase all configurations show NOx emissions ≤ 2 mg/kWh. The Dual-SCR configuration (turquoise line) has the highest cold start NOx conversion capability followed by the Enhanced Stage V + EGH (dark blue) and the Enhanced Stage V system (grey).
For Variant 3 (Stage V + EGH) a heater power variation was performed, and the heater power was increased from the base setting of 2.5 kW to 5 kW (dark blue dotted line). The increased heater power negatively impacts the cumulative NOx tailpipe emissions during the cold phase of the NRTC. Higher heating power accelerates the temperature

increase in the emission control system during the heat-up phase, but it also results in higher NOx engine out emissions compared to tests with lower heating power. Given the short heat-up phase of less than 200 seconds in the cold phase of the NRTC, the elevated NOx engine-out emissions at the start of the cycle cause an overall higher brake specific NOx result in tests with a maximum electric heating power of 5 kW.

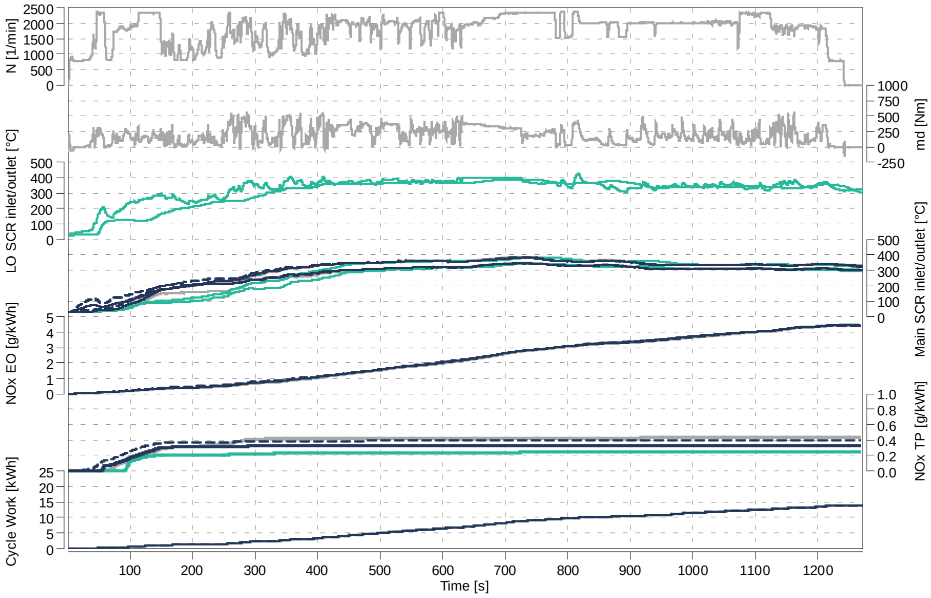

Figure 6: Comparison of NOx emissions for all emission control systems in the NRTC cold

N_2O emissions. All 3 emission control system variants exhibit combined N_2O emission of 30 mg/kWh and lower. The Dual-SCR variant has the lowest N_2O formation as the entire NOx conversion during heat-up and low-load phases and 50 % of the NOx conversion during regular operation happens in the LO-SCR stage including a Ti/V SCR catalyst. However, due to the aged condition of the emission control system, reducing NO_2 to NOx ratios upstream SCR < 50 % and the main SCR being an Fe/Cu Zeolite SCR formulation, the N_2O tailpipe level of the Enhanced Stage V and the Enhanced Stage V + EGH configuration are almost as low as for the Dual SCR variant and sufficient margin to the projected Tier 5f limit of 150 mg/kWh is maintained.

Considering systems certified to the Tier 4f standard as a baseline the demonstrator system achieves a significant reduction of NOx and N_2O emissions with all ECS variants (Figure 7).

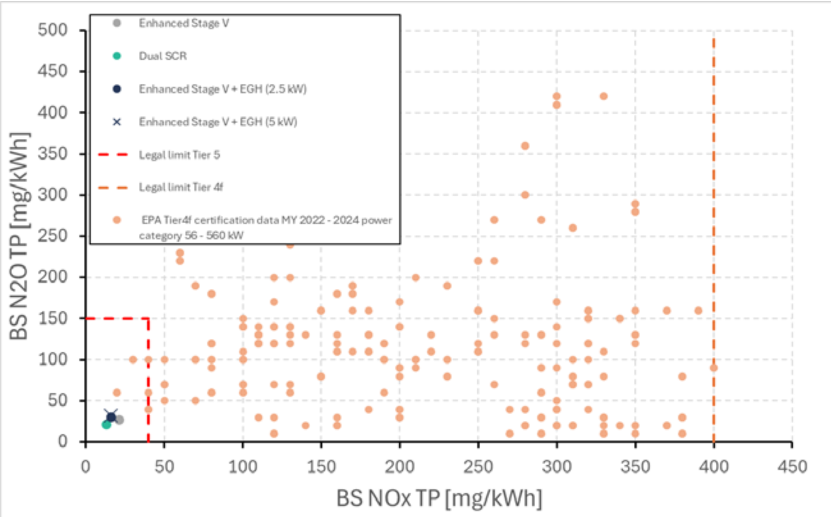

Figure 7: Demonstrator system results on NRTC cold/hot compared to certifcation data

PN10 Emissions. Measurements with the PN-Counter located downstream the DPF and engine out prove that the soot-born PN10 emissions can be filtered with an efficiency > 99.999 % during load profiles with the characteristics as in the NRTC hot or the LLC hot (Table 7).

Table 7: PN10 emissions during NRTC hot and LLC hot

Cycle	PN10 EO	PN10 ds Filter	Filtration Efficiency	PN TP	Urea Particle Formation	Share of Urea Particles
	#/kWh	#/kWh	%	#/kWh	#/kWh	%
NRTC	1.70E+14	4.48E+08	99.9997	2.07E+11	2.07E+11	99.8
LLC	1.62E+14	4.94E+08	99.9997	3.19E+10	3.14E+10	98.5

In Figure 8 the PN10 concentration after the filter and tailpipe, the AdBlue© dosing amount and the SCR temperatures of the main SCR and the LO-SCR stage during the NRTC hot conducted with the Dual-SCR configuration are depicted.

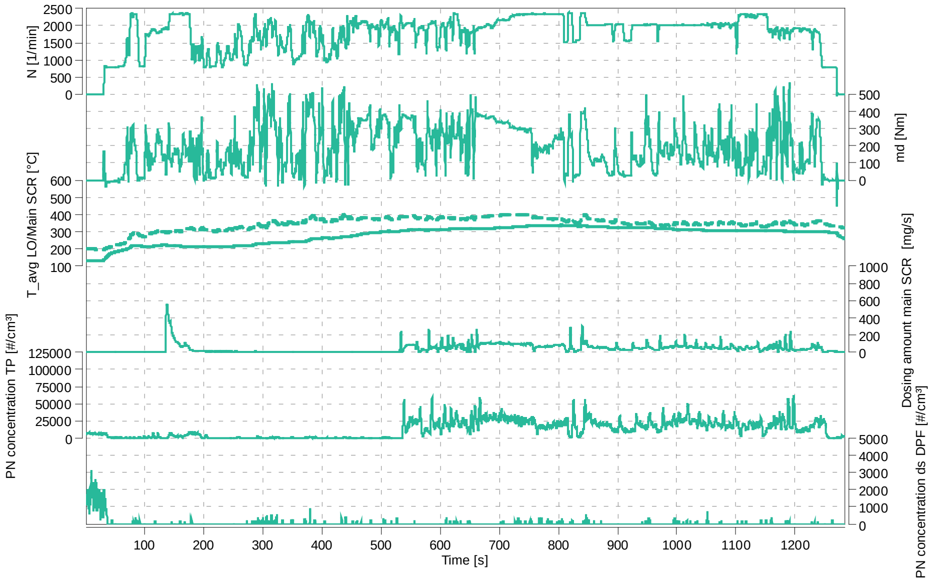

Figure 8: PN Emissions in the NRTC hot (Dual-SCR configuration)

The PN10 tailpipe signal follows the AdBlue© dosing rate of the main-SCR stage proportionally, indicating that most PN10 particles are Urea-based particles. Before the AdBlue© dosing is activated for the second time in the NRTC hot cycle, the PN10 concentration is below 1000 #/cm³. Once the AdBlue© dosing is activated at around 500 seconds cycle runtime, PN10 concentration rises to 20000 – 40000 #/cm³, typical for Urea-born particles at this temperature. The Dual-SCR configuration shows the lowest PN10 level at $8.51*10^{11}$ /kWh, while the other variants have PN10 emissions twice as high. This is because in the Dual-SCR system Urea-born particles formed in the LO-SCR stage are captured in the DPF.

3.2 Ramped Mode Cycle

The main emission results in the RMC cycle are summarized in Table 8. Variant 3 (Enhanced Stage V + EGH) was not tested in this cycle as it is hot started and the temperature in the emission control system is not low enough to trigger the activation of the EGH.

Table 8: Test results in the RMC

ECS	Unit	Variant 1 (Enhanced Stage V)	Variant 2 (Dual-SCR)	Legal Limit Tier 5	Legal Limit Euro 7
Species		Results			
NOx EO	mg/kWh	4010	4717	-	
CO	mg/kWh	0	0	5000	1500
THC	mg/kWh	1	0	80	160
NOx TP	mg/kWh	5	3	40	200
N2O	mg/kWh	21	35	150	200
PM	mg/kWh	<1		5	8
NH3	ppm	<1		10	60
PN10	#/kWh	2.54E+11	2.62E+11	N/A	6E+11

NOx emissions. Both ECSs show similar performance in terms of NOx conversion reaching tailpipe emission levels ≤ 5 mg/kWh.

N_2O emissions. Contrary to the NRTC cycle the Dual-SCR configuration emits more N_2O than the Enhanced Stage V system does. As the temperature measured in the LO-SCR reaches up to 570 °C in the engine´s rated power point, the N_2O formation in the Ti/V SCR increases and the cycle result is higher for the Dual-SCR configuration. Compared to recently published certification data the demonstrator system results are clearly within the NOx/N_2O Tier 5f target window (Figure 9).

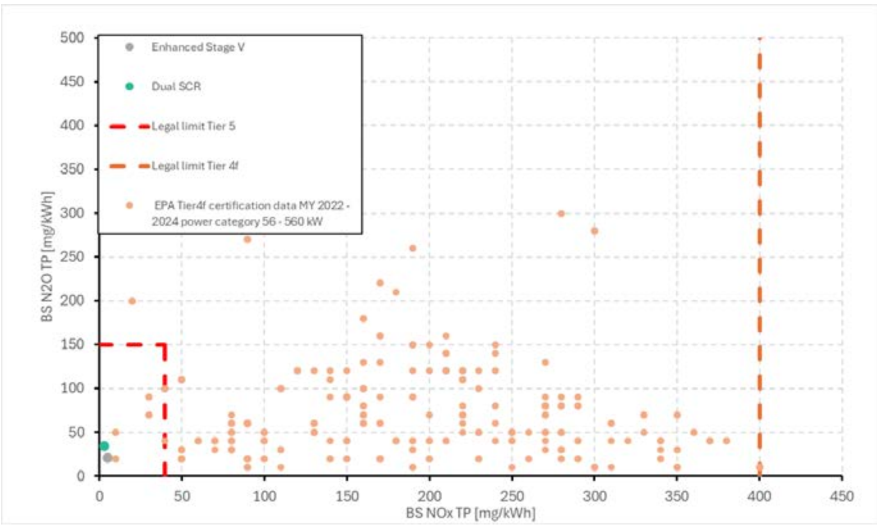

Figure 9: Demonstrator system results on RMC compared to certification data

PN10 emission. Compared to the NRTC Cold/hot the PN10 cycle emission result is in a similar range in the RMC cycle but the nature of the PN10 particles differs. In the NRTC the PN10 particles mostly originate from the AdBlue© dosing while in the RMC the species is mostly composed of soot particles. Measurements with the Particle Counter downstream the filter and tailpipe show a similar level of PN10 emissions (Table 9) indicating that the Urea-born particle contribution to the overall PN10 emissions is much less than in the NRTC. Due to the higher temperature, especially in the rated power point, the soot oxidation in the filter increases causing the typically associated PN10 slip. Furthermore, the exhaust gas temperature after turbine (~ 410 °C) in the cycle is above the peak temperature range of Urea particle formation (300 - 350 °C).

Table 9: PN10 emission in the RMC cycle

Cycle	PN10 EO	PN10 ds Filter	Filtration Efficiency	PN TP	Urea Particle Formation	Share of Urea Particles
	#/kWh	#/kWh	%	#/kWh	#/kWh	%
RMC	1.10E+14	3.60E+11	99.6730	4.22E+11	6.23E+10	14.8

3.3 LLC hot

The Low-Load-Cycle with its NOx limit of 60 mg/kWh and the 1200-second-long idling period after around 300 seconds cycle runtime, demands either high exhaust gas temperature management efforts from the engine or additional heat sources directly in the emission control system to minimize the NOx slip during and after idling. The results obtained with the 3 emission control system variants are displayed in Table 10.

Table 10: Results in the LLC hot

ECS		Variant 1 (Enhanced Stage V)				Variant 2 (Dual SCR)	Variant 3 (Enhanced Stage V + 2.5 kW EGH)	Legal Limit Tier 5
Airpath		standard	adapted	adapted	adapted	adapted	standard	
Calibration		adapted	standard	adapted	adapted	standard	standard	
Idle Troque	[Nm]	44	44	44	66	44	44	
Species	Unit	Results						
NOx EO	mg/kWh	4725	6121	4848	4591	5707	4948	
THC	mg/kWh	15	9	7	6	6	7	190
NOx	mg/kWh	372	292	80	8	17	0	60
CO2	% relative to baseline	100	100	100	108	100	105	

The tests conducted with the Dual-SCR system (17 mg/kWh) and the Stage V + EGH system (0 mg/kWh) show NOx tailpipe results below the Tier 5f Low-Load-Cycle limit. The alternative airpath was deactivated for the test with the Exhaust Gas Heater to demonstrate a concept with minimum exhaust gas temperature management effort from the engine. For the Enhanced Stage V configuration, the alternative airpath approach did not deliver sufficient exhaust gas temperature during the idling period to reach the Tier 5f NOx limit and hence calibration adaptations in and around the idle point were performed with the aim of increasing the exhaust gas temperature level. As a first measure the EGR rate was increased from 2% to 17 % and secondly the combustion timing was retarded by 3-degree crank angle. A combination of these measures plus the impact of the alternative air path concept enabled a reduction of the NOx tailpipe emissions to 80 mg/kWh. Time based data are depicted in Figure 10 (the same colour code as in Figure 6 is used) and identify the idling period starting at around 300 seconds cycle runtime as the most critical phase of the cycle. NOx slip to the tailpipe predominantly occurs during and after this idling period.

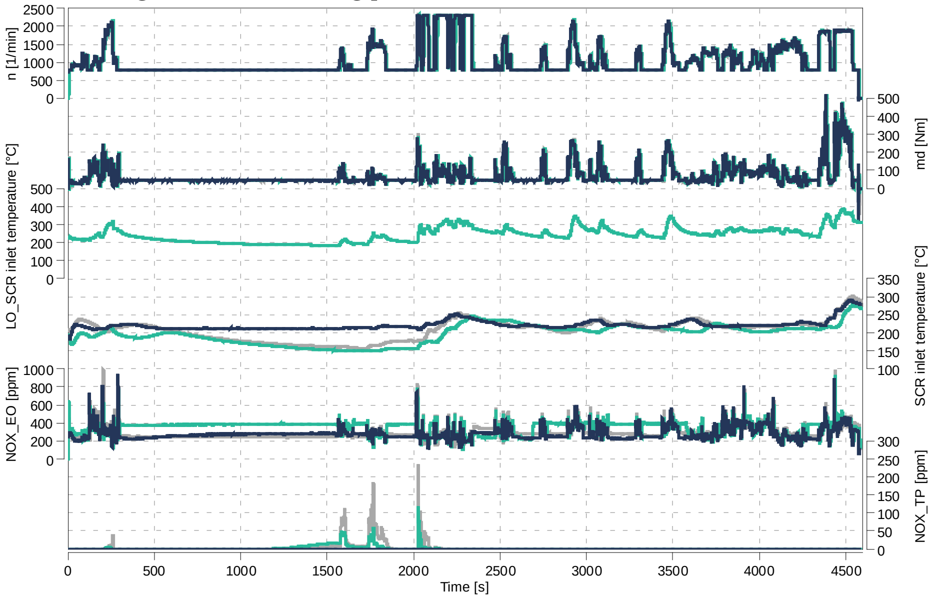

Figure 10: NOx emission/SCR temperature for the 3 different ECS in the LLC h

In an additional experiment with the Enhanced Stage V configuration the torque in the idle point was increased by 50 % from 44 to 66 Nm, leading to a further increase of the exhaust gas temperature and consequently a lower NOx tailpipe result of 8 mg/kWh. Besides the NOx and THC emission the relative CO_2 emission for the different tests compared to a baseline measurement are listed in Table 10. The airpath and calibration adaptations have a negligible impact on the overall cycle CO_2 emissions. For the test with the increased idle torque an 8% CO_2 increase was calculated by dividing the CO_2 emission measured in the cycle over the cycle work of a test with nominal idle torque. The Exhaust Gas Heater increases the CO_2 cycle result by 5% in Table 10 compared to the baseline measurement, but the heating strategy is observed to be too aggressive given 0 mg/kWh NOx result. A corrected CO_2 increase of 1.5% is calculated considering an optimized heating strategy and the same NOx tailpipe level as in the test with the increased idle torque (i.e. 8 mg/kWh).

3.4 LLC cold

To test the characteristics of the ECS variants in a load profile with low engine load and cold start conditions the LLC was run as a cold started cycle. Although the cold-started low-load cycle in the current Tier 5 proposal has no legislative relevance, the authors decided to evaluate such a test as a worst-case scenario. By using the EHC with a heating capacity of 5 kW, NOx emissions below 200 mg/kWh were achieved. In contrary to the NRTC cycle, with a higher average engine load, the increased heater power leads to lower NOx emissions as the enthalpy coming from the engine is insufficient to heat the SCR system up properly.

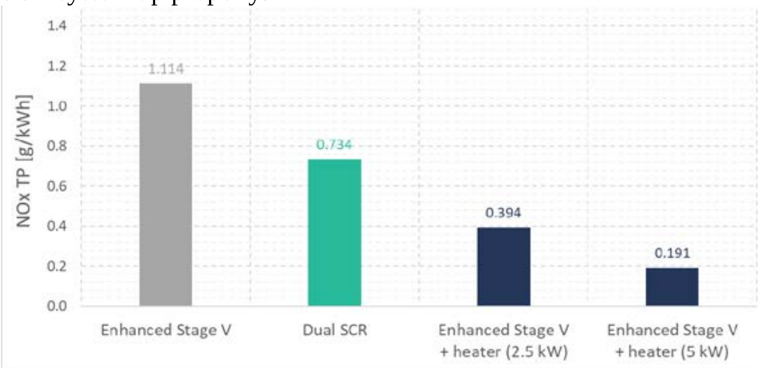

Figure 11: LLC cold started; NOx Tailpipe Emissions

3.5 In-use load profiles

In the hot started in-use load profiles representing different applications (wheel loader, excavator, forklift and bulldozer) consistently low NOx emissions levels were demonstrated with the Enhanced Stage V and the Dual-SCR configuration. Variant 3 was not measured on these hot start tests. Since certain species, such as N_2O and PN10, will not be restricted in in-use load profiles under the Tier 5f regulation, the results for these species are compared to the Euro 7 limit values. The cumulative results in Table 11 and Table 12 show both ECSs being capable to reach cumulative NOx emission $\leq$ 15 mg/kWh in all in use cycles. Like in the NRTC Cold/hot the Dual-SCR configuration exhibits generally lower N_2O and PN10 emissions. In the cycles with low average engine load the N_2O emissions increase up to 197 mg/kWh in the wheel loader cycle for the Enhanced Stage V concept. Due to the low space velocity in the DOC and DPF the NO_2 to NOx ratio upstream SCR increases causing higher N_2O formation on the Fe-Zeolite SCR section of the main-SCR. This effect is expected to be more pronounced for a system in degreened condition due to the higher NO_2 to NOx ratio upstream SCR.

Table 11: Cumulative emission results measured with the Dual-SCR configuration

ECS		Dual-SCR				Legal Limit Euro 7
Cycle		Excavator	Bulldozer	Fork Lift	Wheelloader	
Species	Unit	Results				
NOx EO	mg/kWh	3878	4183	4938	5677	-
CO		0	0	0	0	1950
THC		0	0	0	10	80
NOx TP		0	2	0	1	260
N2O		20	26	93	84	260
PN10	#/kWh	1.22E+11	8.05E+10	2.95E+10	1.16E+10	-
Average engine load	%	30	50	15	8	
Average T LO SCR	°C	386	430	307	245	
Average T main SCR	°C	327	380	239	203	

Table 12: Cumulative emission results measured with the Enhanced Stage V configuration

ECS		Enhanced Stage V				Legal Limit Euro 7
Cycle		Excavator	Bulldozer	Fork Lift	Wheelloader	
Species	Unit	Results				
NOx EO	mg/kWh	5207	3780	4680	6129	-
CO		0	0	7	0	1950
THC		0	0	1	13	80
NOx TP		5	2	0	15	260
N2O		40	19	126	197	260
PN10	#/kWh	1.84E+11	1.11E+11	1.09E+11	8.75E+10	6.00E+11
Average engine load	%	30	50	15	8	-
Average T main SCR	°C	374	386	246	220	

3.6 Tests with Hydrotreated Vegetable Oil

To demonstrate the concept of a CO_2 neutral, Tier 5f ready, powertrain for the NRMM sector, the NRTC Cold/hot was repeated on 100% Hydrotreated Vegetable Oil (HVO) fuel with the enhanced Stage V configuration, see Table 13. In the test with HVO reduced NOx engine out, NOx tailpipe and CO_2 emissions were measured. N_2O and PN10 emissions are close to the test result with EN 590 fuel.

Table 13: NRTC cold/hot results with EN590 and HVO

ECS	Unit	Variant 1 (Enhanced Stage V)			Legal Limit Tier 5	Legal Limit Euro 7
Species		Results		Difference		
Fuel	[-]	EN590	HVO	[%]		
NOx EO	mg/kWh	4013	3668	-9	-	
CO		6	9		5000	1500
THC		1	2		80	160
NOx combined		21	19	-12	40	200
N2O		27	30		150	200
NH3	ppm	<1			10	60
PN10	#/kWh	1.96E+11	1.84E+11		N/A	6E+11
CO2	g/kWh	756	737	-3	733.6	

4 Summary & Conclusion

Tier 5final and Euro7 regulatory limits were demonstrated with all 3 emission control systems in the NRTC cold/hot. The Dual-SCR system and the Enhanced Stage V + EGH system show benefits in reduction of cold start NOx emissions. Additionally, the Dual-SCR configuration achieves lower N_2O emission compared to the single-SCR concepts due to the high N_2 selectivity of the LO-SCR system (Ti/V SCR technology). Tailpipe PN10 emissions are lower as the Urea-born particles – being the main PN10 constituent in the NRTC cycle - formed upstream the LO-SCR are captured in the DPF. In the RMC the Enhanced Stage V and the Dual-SCR system were tested. While the NOx emissions are similar for both systems, the Enhanced Stage V system emits less N_2O compared to the Dual-SCR configuration, as the N_2O formation on the LO-SCR increases in operating points with exhaust gas temperature > 450 °C. With soot-particles being the primary constituent of tailpipe PN10 emission the system architecture has a limited impact on the PN10 cycle result.
The hot started low-load-cycle (LLC) is the most challenging Tier 5f certification cycle due to a ~1200s idling period, causing exhaust gas temperatures to drop to critically low levels (200°C and lower). The Dual-SCR and Enhanced Stage V + heater configurations meet the Low-Load-Cycle NOx limit whereas the Enhanced Stage V system shows NOx emissions just above the projected Tier 5f limit. With improved exhaust gas temperature management measures (e.g.: exhaust flap) lower NOx TP results could be reached. The Enhanced Stage V + Exhaust Gas Heater system shows the highest capability to maintain exhaust gas temperature above 200°C regardless of engine conditions. This is also the case in an even more challenging cold-started low-load cycle.
Hot started in-use cycles representing various applications (wheel loader, forklift, bulldozer, excavator) show pollutant emission levels well below Tier 5f/Euro 7 limits when tested with Dual-SCR and Enhanced Stage V configurations.
NRTC cold/hot and LLC h cycles tested with HVO instead of EN590 result in similar tailpipe emission levels along with reduced NOx engine out and CO_2 emissions.
The test results gathered in this study prove that state-of-the-art engine and emission control technology can bring emissions of a representative NRMM Diesel engine below Euro 7 and Tier 5f regulatory limits in laboratory and real-world operating profiles. Considering the well-to-wheel CO_2 reduction potential of up to 90% offered by HVO, a viable and sustainable low-emission powertrain concept can be developed for the NRMM sector.

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