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Year: 2020

Version: Accepted manuscript

Please cite the original version:

Lauren, M., Karhu, T., Niemi, S., Laivola, M., Ekman, J., & Spoof-Tuomi, K., (2020). Different methods to improve the exhaust gas temperature in modern stage V off-road diesel engine over transient emission cycles. *Sae technical papers*. https://www.sae.org/publications/technical-papers/content/2020-01-0903/

DIFFERENT METHODS TO IMPROVE THE EXHAUST GAS TEMPERATURE IN MODERN STAGE V OFF-ROAD DIESEL ENGINE OVER TRANSIENT EMISSION CYCLES.

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Abstract

This paper presents several methods to improve the exhaust gas temperature of a modern diesel engine. A high exhaust gas temperature is needed to improve the after-treatment system efficiency and particulate filter regeneration in low engine loads. This study is based on experimental measurements of two Stage 5 level off-road diesel engines. The effect of the different heating methods determined over steady state runs and emission and performance are presented with standard emission transient test procedure (NRTC). In the first step of the study, an intake air restriction and an exhaust gas restriction method are compared. The intake restriction produces better fuel economy over the measuring cycle. However, with the exhaust restriction, higher exhaust gas temperature can be achieved in low engine loads. In the second phase of study, the intake air restriction method was implemented in the research engine. In addition, active waste gate controlling, and injection retardation methods were taken in use for heating purposes. The engine performance was determined with normal calibration and with high exhaust temperature calibration. The differences to the exhaust temperature, engine performance and emission were presented in transient emission cycle NRTC.

Introduction

Modern heavy-duty diesel engines are equipped with complex exhaust gas catalytic systems. Typically, EU Stage 5 compliant off-road diesel engines are equipped with Diesel Particulate Filters (DPFs) and Selective Catalytic Reduction (SCR) units. The current emissions legislation demands that the after-treatment system must also be effective at loads with low exhaust temperature.

In the literature references the technical variations in modern on-road diesel engines were discussed widely. References [1] and [2] shows that, off-road engines typically used the same kind of after-treatment technology as on-road vehicles. An effective working temperature for the catalytic converters is different with the different units. Typically, SCR-systems are effectively within a 250…450 °C temperature range and DPF regeneration temperatures are within a 300…400 °C range [3]. To secure the converting efficiency of the catalyst, within the normal use of the engine, the exhaust gas temperatures should be increased in low engine loads.

In the reference, [4] presents comparisons of different technological approaches of heavy-duty diesel engines. The NOx emission levels of modern engines can be reached with SCR only or using Exhaust Gas Recirculating (EGR) alongside the SCR method. According to [4], the EGR can be used for SCR heating purposes also. Some manufacturers, such as Volvo, use the EGR for SCR heating in cold start. [1]. The use of EGR also decreases NOx emissions after the cold start phase and that can decrease the efficiency demands of the SCR system in these operating areas. References [1] and [4] present a table that combines the typical efficiency levels of the SCR system and EGR rates in different approaches. When the SCR-only strategy is used, the efficiency level of SCR is typically over 96%, and sophisticated thermal management is needed. If the EGR is used without EGR cooling, the SCR efficiency is, according to the reference, within the level 94…96%.

Several different methods to improve the exhaust gas temperature instead of EGR have also been shown in the literature. Some of these include fuel injection retarding, late post injection (LPI) [5] and different kinds of exhaust gas burners. With burners, a high temperature increase can be achieved quickly after the cold start, but the systems are quite complex and fuel consumption will be high as well [6]. The study [7] present a fuel processor, which can improve the exhaust temperature by injecting the fuel into the exhaust gas or burning it in the processor chamber.

In a study [8], determined the effect of exhaust back pressure on marine engine performance. In this reference, noticed that the valve timing principles strongly affect the performance in different exhaust back pressures. In a conventional marine engine with high valve overlapping and constant pressure, turbocharging increased the sensitivity of air, decreasing when exhaust back pressures increased. It can be concluded that the effect of air restrictions depends on the different technical approach of the engine.

Several papers [9] and [10] show that exhaust throttling is combined with the use of an LP-EGR. In reference, [11] a cylinder deactivation method, that was a more efficient way to increase the exhaust temperature than air path controlling by turbocharger or injection delaying. They also noticed that 80% of the fuel consumption increase can be avoided, with cylinder deactivation compared to the other methods.

In the reference [12], studied how the intake air temperature affected the exhaust temperature when intake air was cooled by using an air conditioning unit. Reducing the intake air temperature by 20…40 °C, increased the exhaust temperature to 30…50 °C, and at the same time, the fuel consumption decreased by 2.6% due to the lower intake air temperature. If the cooling power of the air conditioning unit is considered, the total net advantage was 1.5%.

Also, the efficiency of the SCR catalyst is under development. References [13] and [14] presents that, using the different SCR chemistry the efficient temperature window of the SCR catalyst can be wider and the conversion efficiency is acceptable in low exhaust gas temperatures. The reference [15] present, a method to improve a heavy-duty diesel engine's fuel economy, by affecting the pumping losses over a transient cycle. In this reference, intake air restriction is used for controlling the EGR circulation levels. This affects the exhaust gas temperature in different operation points.

This paper focused in the air path controlling with using the intake and exhaust gas controlling techniques. The intake air restriction was implemented with injection timing retardation and with active wastegate into the research engine. Based on this literature survey, in this study, the exhaust temperature increasing of 100…200 °C was targeted to achieve efficient operating temperature of catalytic converters. The effects of intake and exhaust restriction methods on engine performance, emissions and fuel consumption are presented. Also, the performance drawbacks are presented.

Experimental set-ups

This experimental research was conducted with 6-cylinder and 4-cylinder heavy-duty diesel engines. The technical characteristics of these engines and equipment are presented in table 1. This kind of engines are typically used in agricultural tractors and combined harvesters. Both engines were connected to an eddy current dynamometer. The controlling system of the dynamometer and the engines were based on NI Labview software and the PXI hardware system. The used emission measurement units and other test stand equipment are shown in table 2.

Table 1. Test engine and equipment

Engine type	High speed, 6, cylinder turbocharged diesel engine	High speed 4 cylinder turbocharged and intercooled engine
Brand	AGCOPower 74 AWF	AGCOPower 49 AWF
Rated Power	125 kW / 1950 rpm	122 kW / 2100 rpm
Bore / Stroke	108 mm / 134 mm	108 mm / 134 mm
Turbocharger and Intercooling	1-stage turbocharger with pneumatic waste gate. Intercooling	1-stage turbocharger with electronic controlled waste gate. Intercooling
Fuel injection type	Common Rail system, solenoid injector.	Common Rail system, solenoid injector.
NOx reduction catalyst	No EAT used.	Oxidation catalyst (DOC)

Table 2. Equipment for exhaust emission measurement

Nitrogen oxides	Eco Physics CLD 822 M
Carbon monoxide	Siemens Ultramat 6
Total hydrocarbons	JUM VE 7
Carbon dioxide	Siemens Ultramat 6
Oxygen	Siemens Oxymat 61
Ammonium	Neogas Laser –based analyzer
Particulate mass	AVL MSS 483
Diesel smoke	AVL 415 S G002
NOx sensors for SCR system	Siemens VDO
Fuel consumption	Emerson Coriolis –based sensor
Combustion Air consumption	ABB Sensyflow

The Intake and exhaust restriction were implemented by electronically controlled valves in the intake and exhaust lines according to figure 1. The Intake restriction (IAR) valve was connected after the charge air cooler and before the intake manifold. The exhaust restriction (EXF) flap was mounted after the turbocharger turbine. The principles of an active waste gate are also shown in figure 1.

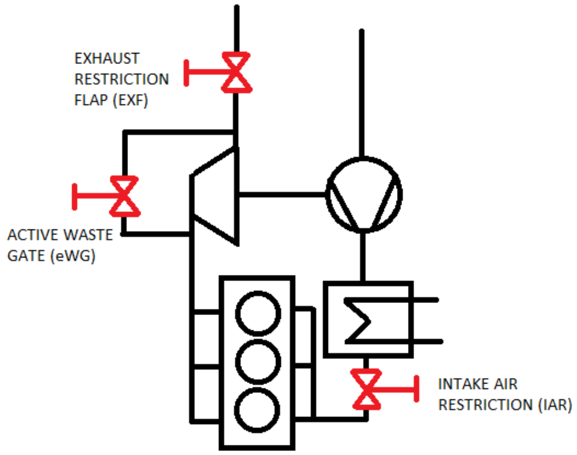

Figure 1. Intake and exhaust restriction valves and active waste-gate

Comparison with the intake and the exhaust restriction in steady-state engine load points

In the first phase of this study, the effect of the IAR and the EXF to engine performance and exhaust temperature were determined by using the 74 AWF engine. Typically, in high engine loads, the air to fuel ratio is critical and the temperature of the exhaust gas is also sufficient to ensure the high catalyst efficiency. For that reason, it was decided that the study will focus on the low engine loads (≤ 50%). The rated speed of the engine was 1950 rpm and the most interesting speed range is within 1200 rpm to 1950 rpm, with load points between 10…50% of maximum loads where these measurements were carried out. The reference exhaust gas temperature, without any restrictions, in the load range 10….50%, is shown in figure 2. This graph show that the exhaust gas temperature is mainly below 250 °C at 30% load and lower and 300 °C level are nearly 45% engine load.

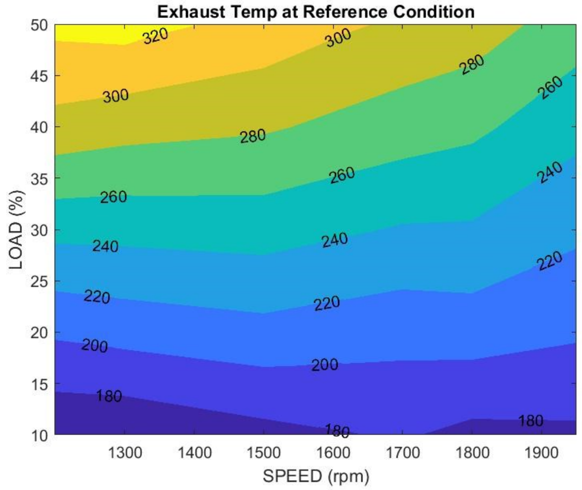

Figure 2. The exhaust gas temperature in reference condition of engine,

The engine performance data was collected at several engine speed and load points in different valve positions. The IAR and EXF sweeps were conducted separately. Figure 3 presents the exhaust gas temperature, exhaust gas particulate mass and fuel consumption disadvantage, in the function of restrictions in one engine load point. Figure 3 shows, that the IAR is more effective to increase the exhaust gas temperature than the EXF. However, the smoke emission increased rapidly when the IAR throttling was above 400 mbar. Also, there are less fuel consumption disadvantages when restrictions were below 400 mbar when the IAR was used. However, the fuel consumption was lower in between 200…300 mbar, and with the restriction near 400 mbar the exhaust gas temperature was also higher.

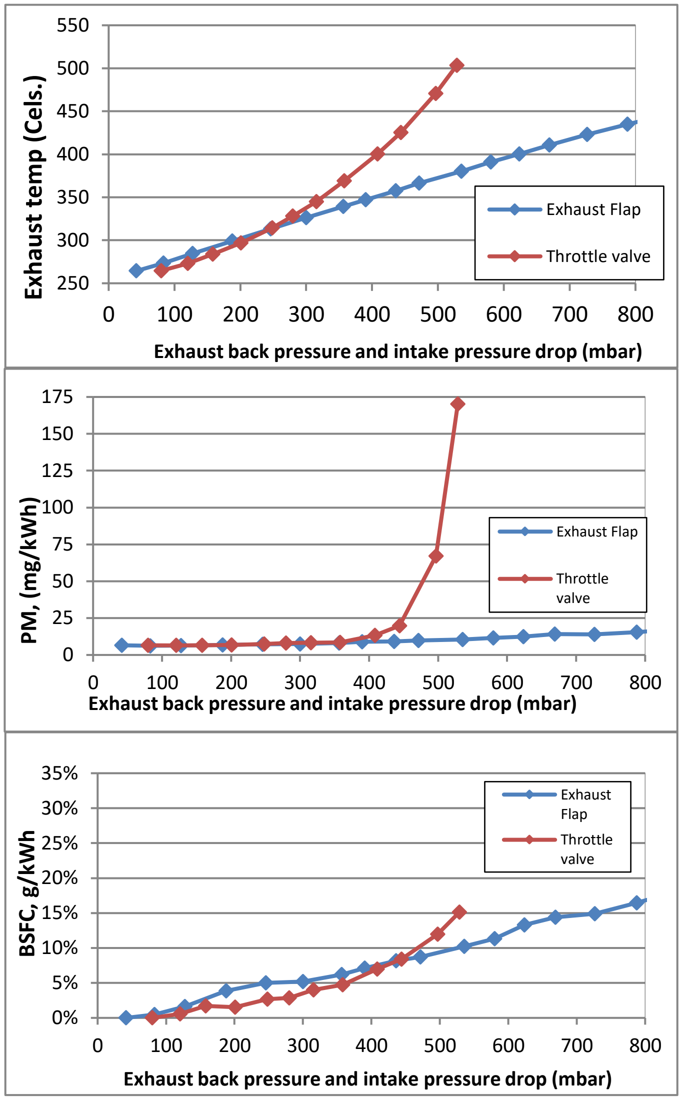

Figure 3. The exhaust gas temperature, particulate emission and fuel consumption changes in the function of intake and exhaust line restriction pressure at engine speed 1800 rpm and load 40% of maximum

With the IAR method, the engine running was unstable in high restriction levels and the engine produced high hydrocarbon emissions (Figure 4). This may be the result of a too low intake pressure in the engine cylinder, then it might be possible that the ignition of fuel is unsatisfactory.

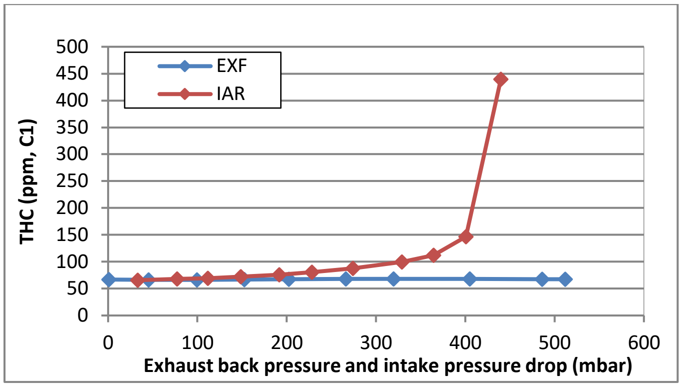

Figure 4. The hydrocarbon emission when using IAR and EXF methods to improve the exhaust gas temperature. Speed was 1300 rpm and load was 10% of the maximum.

To see the restriction effects in the wide speed range, it was decided to focus on the point where the exhaust temperature was increased to 100 °C without the restrictions. Figures 5 and 6 show the fuel consumption and particulate emission results where the increase to 100 °C was achieved in every load and speed point of the engine operating area. The temperature data points were interpolated linearly from the experimental data to correspond the temperature increase to 100 °C.

Figure 5 presents the fuel consumption disadvantages at a lower level in all speed and load points when the IAR was in use. On the other hand, smoke increased more rapidly with the IAR than with the EXH. Typically, in 50% and 40% load points, the fuel consumption disadvantages were within 4…8% with the IAR and within 7…13% with the EXF. When the engine power output was low (Figure 5), the fuel consumptions were at a higher level for the reason that it was calculated as relative change in the reference situation. In 20% loads, there were increases in the fuel consumption, such as 3…12% with the IAR and within 16…23% with the EXF.

The particulate emission increase with the intake throttle was within 0…2% and with the exhaust flap between 0…1% (Figure 6.). In some measuring points, PM emission decreased when compared to the no restriction point. This may be caused by the phenomenon, which is presented in Figure 4. The ignition of the combustion process is unstable due to low intake air pressure, and smoke decreased but unburned hydrocarbons rose rapidly. The PM emission increasing was quite limited and at many points the PM emission was lower than without restrictions.

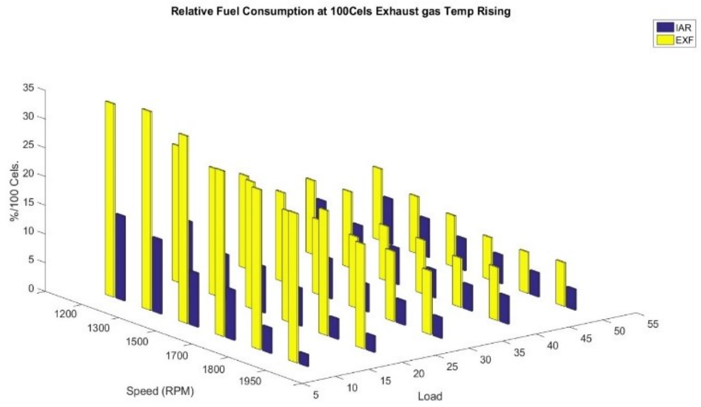

Figure 5. The relative fuel consumption changes in different load points with the IAR and EXF methods.

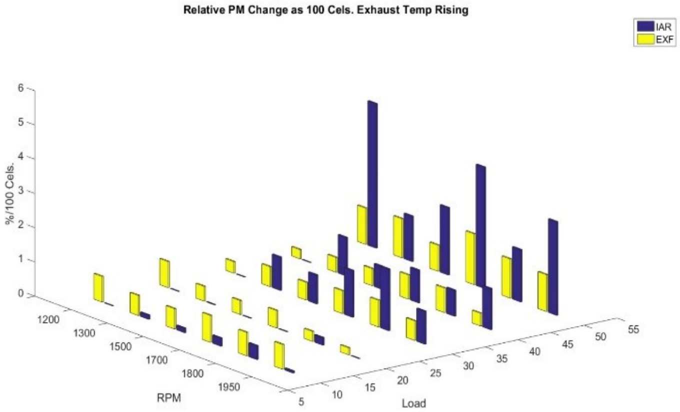

Figure 6. Relative PM change in different engine load points with the IAR and EXF methods

Air Management With Intake Air Restriction, Waste-Gate Controlling And Injection Timing

In the first step of this study, is noticed that the IAR method was effective to improve the exhaust temperature at low loads. This system was implemented in the next research engine. This engine type was Agco Power 49 AWF. The main differences with these engines were that the 49 engine was 4-cylinder and 74 AWF engine was 6-cylinder. In the first step of the study, intake air restriction proceeded without opening the WG port. This may lead to disadvantages in higher loads where charge pressure is higher. To avoid this effect, the turbocharger was equipped with an electronical wastegate controller (WG). In high engine loads, the WG was opened first to decrease the charge pressure and after that, the air flow was controlled with the IAR flap (Figure 7.)

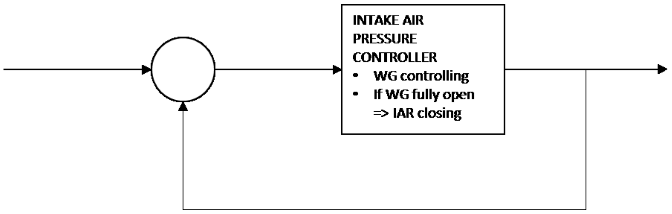

Figure 7. Schematic figure of WG and IAR controlling principle.

The IAR method with WG control and the fuel injection timing retardation were determined separately. All these methods were combined and two ECU calibrations were performed over the engine operating range. The basic calibration was normal engine operation and no IAR was used. This calibration is referred to as REFCAL. The high exhaust temperature calibration is referred to as HTCAL. The engine operation in the wide range was studied. The important differences in REFCAL and HTCAL are shown in figures 8 and 9. The injection timing retardations in HTCAL were in the range -4…12 deg compared to REFCAL, Figure 8. Increasing the injection advantage leads to stable engine running, in high engine loads. The WG position and IAR rate were controlled by charge air pressure at intake manifold. The intake manifold pressure decreased 0.05…0.81 bar in different points and engine air consumption was 5…45 % lower.

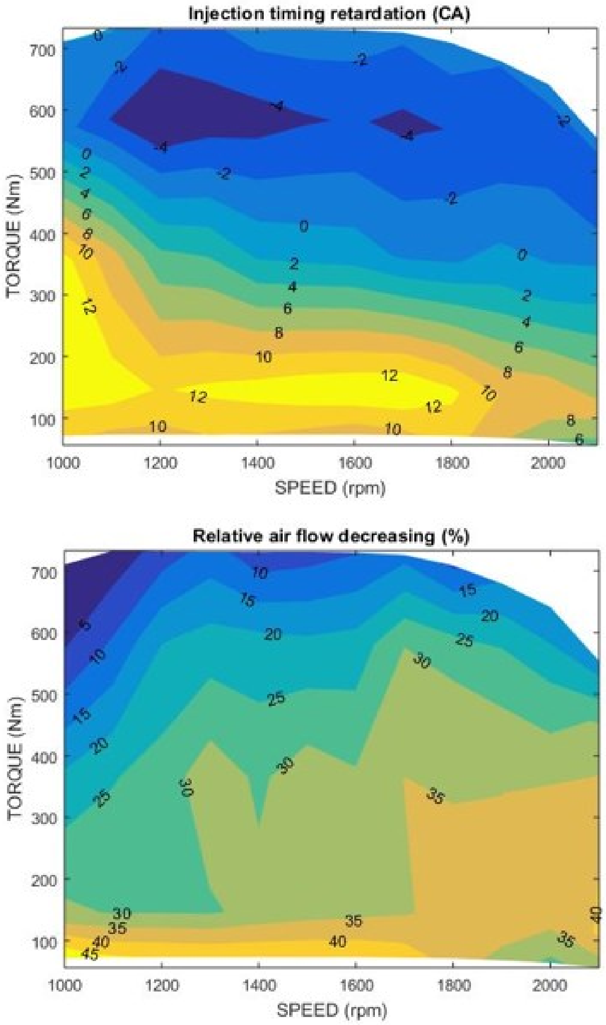

Figure 8. HTCAL injection timing and airflow differences compared to REFCAL ECU settings

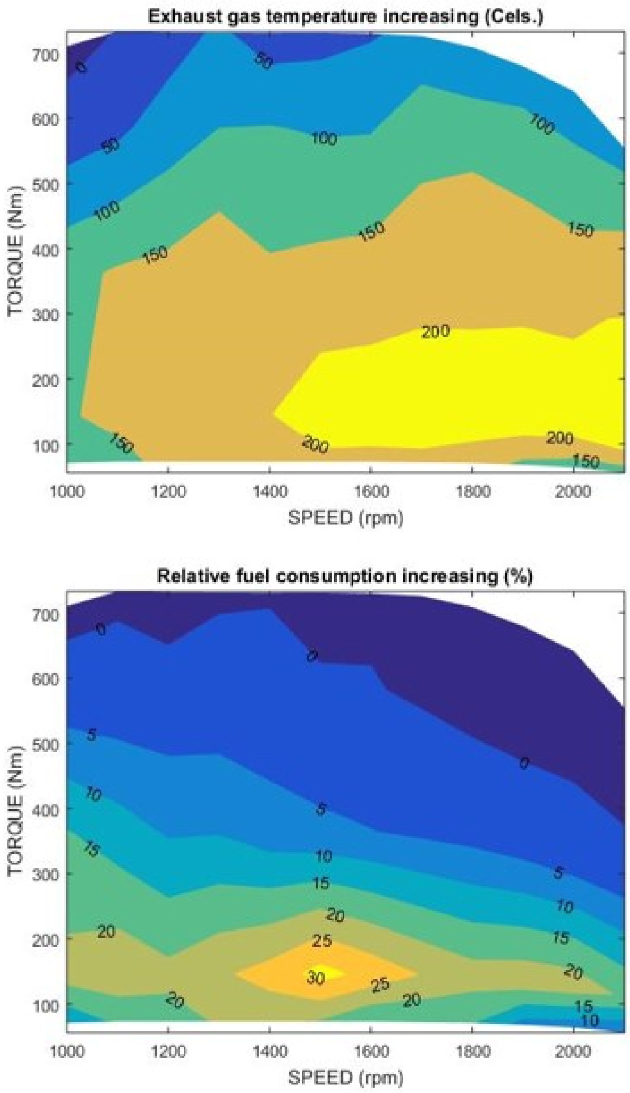

Figure 9. The exhaust gas temperature and fuel consumption relative increasing in engine operating range when HTCAL was used

Figure 9 shows the increase in exhaust gas temperature and fuel consumption penalty in different engine calibrations. In a speed range above 1400 rpm and load area 10…50%, the exhaust temperature increased at 200 °C and in a wide area also over 150 °C. In this operation area, the fuel consumption increased by 5…31%.

After the steady operation, area mapping of the transient NRTC emission cycles were ran and the HTCAL effect on emissions and exhaust gas temperatures was recorded. Table 3 shows exhaust gas emissions over the NRTC cycle with both ECU calibrations. These results were recorded as exhaust pipe emission so the EAT system is not determined. The NOx emission decreased when HTCAL control was used. On the other hand, the HC and CO emission increased. The fuel consumption also increased by 2.9%.

Table 3. Exhaust gas emissions over NRTC cycle in two different ECU calibrations without EAT.

	NOX	HC	CO	SFC	MSS
	g/kWh			rel.	
REFCAL	6.43	0.18	0.27	100.0%	100%
HTCAL	5.47	0.53	0.85	102.9%	240%

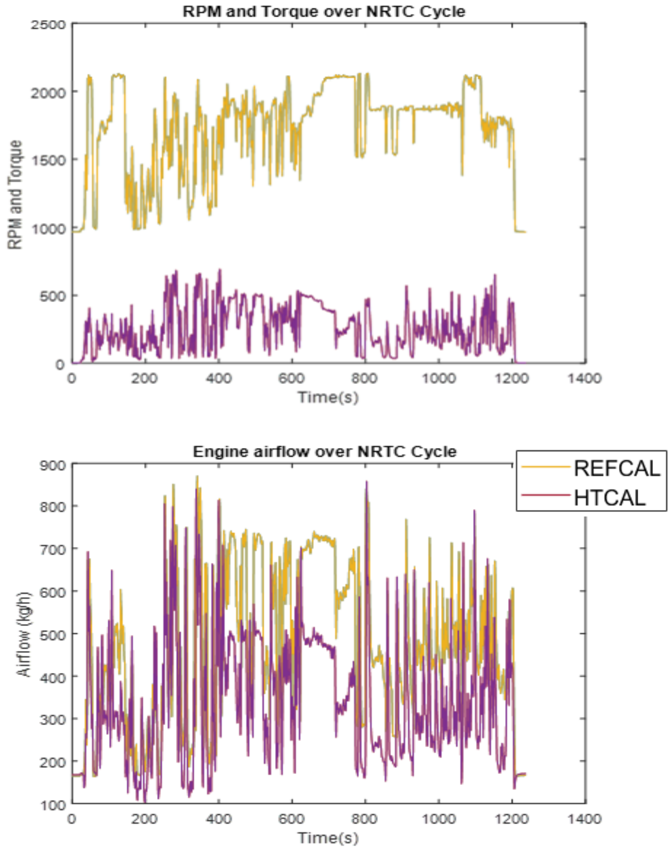

Figure 10. The speed, torque and engine airflow with two-engine calibration method.

The HTCAL calibration decreased engine airflow and lowered the A/F ratio significantly. The lack of air lead to increasing particulate emissions as can be seen in graph 11.

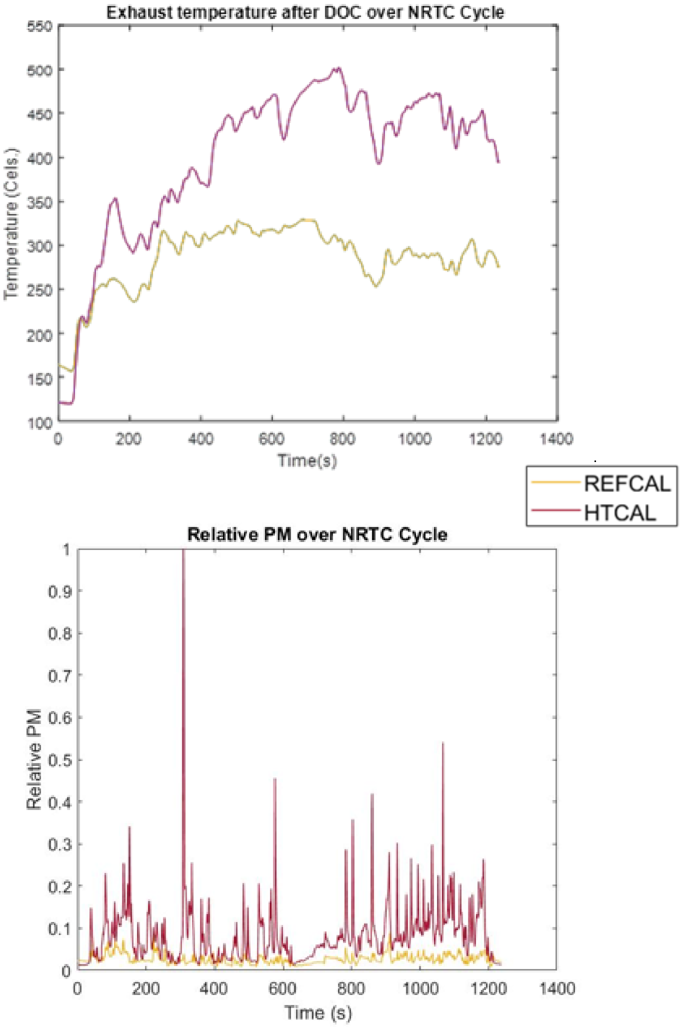

Figure 11. The exhaust temperature and relative PM over NRTC cycle.

With these ECU calibrations, exhaust gas temperature level that is 50…150 °C higher can be reached over the NRTC cycle. The main drawbacks were nearly 3% higher fuel consumption and 140% higher particulate emission. Although, in these test runs the SCR system nor DPF system were not fully used, it can be stated that due to the higher temperature the HTCAL may improve the SCR and DPF operation conditions significantly with moderate fuel and emission increasing.

DISCUSSION

The main observations from the experimental research were that IAR and EXF methods have a different kind of impact on the engine performance. The IAR methods can improve the exhaust temperatures in some load points, but on the other hand, the engine run becomes unstable in high restriction levels. Otherwise, the EXF method increased exhaust temperatures effectively and the engine running was stable. With EXF, the fuel consumption increased faster than with the IAR method. However, increases in PM emissions were lower with EXF methods than with IAR.

Reference [16] present the effect of the intake air throttling results in an experimental study and simulation. In the experimental part of the study, intake throttling was maintained between the turbocharger compressor and the intercooling. The exhaust throttle was installed between engine and the turbocharger turbine. When compared at 4 bar BMEP engine load point, the intake air restriction decreased the lambda from approx. 2.8 to 2.0 and then the exhaust temperature increased from 211 °C to 477 °C. On the other hand, the fuel specific consumption increased from 245 g/kWh to 265 g/kWh (approx. 8%). It seems that fuel consumption drawbacks were at a similar level as in this study.

Reference [17] present several methods to improve the exhaust gas temperature. They noticed that when the intake throttling was used in a 7.1 l diesel engine at low loads, the exhaust gas temperature increased 120…150 °C at maximum throttling. This affects approximately 10…17% fuel of the fuel consumption penalty. Compared to the results of this study, it seems that fuel penalty has increased more. [17] also presented the effects of fuel injection timing and injection pressure on the exhaust temperature and fuel consumption. These measures effect on the temperature was moderate. The main conclusion of this reference was, that in low and middle engine loads, the intake throttling, and injection timing retardation were an efficient way to increase exhaust temperature. However, the post injection method was more efficient.

Reference [18] presents different control strategies for heavy-duty diesel engine exhaust gas temperature management. This paper compares late intake valve closing timing (LIVC) to several other techniques. Intake throttling seems to be a more effective method to improve exhaust gas temperature than the intake timing and the internal EGR. The conclusion of Guan's study, is that intake throttling was effective in increasing the exhaust temperature by 42 °C. This leads to a 7.2% fuel consumption disadvantage and slightly higher NOx emissions. The fuel consumption changes of [18] were higher than in this study and the NOx emission changes were the opposite when compared [18] results to this study. A possible difference in these two studies can be different valve opening timing. In [18] paper, the research engine was an internal EGR engine, contrary to AGCOPower engines in this study, which were not using internal or external EGR.

CONCLUSIONS

Based on the performed results, the following conclusions could be drawn:

1. With the IAR method and at a lower air restriction level, the exhaust temperature increase was higher and the fuel consumption disadvantage was lower when compared to the EXF method.
2. The PM emissions were significantly lower with the EXF method, but the fuel consumption increase was significantly higher than with the IAR method.
3. At low engine loads and very high (> 400 mbar) restriction level, the engine running was unstable, and PM and HC emission increased significantly with the IAR method.
4. When the IAR method was implemented in the engine ECU with active waste gate and injection timing methods, the ECU calibration (HTCAL) could be achieved, which increased the exhaust temperature 50…200 °C in the wide operation area of the engine.
5. With this HTCAL calibration, the exhaust temperature was 50…200 °C higher over the NRTC emission cycle and fuel consumption increased by 2.9%.
6. The engine out NOx emission decreased with the high temperature ECU calibration and particulate mass increased significantly when HTCAL settings were used.

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Acknowledgement

This study was performed in the Engine and Powertrain Laboratory of the Turku University of Applied Sciences and with co-operation of AGCO POWER Inc. at and University of Vaasa Engine Laboratory.

Definitions/Abbreviations

DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
SCR	Selective Catalytic Reduction Unit
IAR	Intake Air Restriction
EXF	Exhaust Line Restriction Flap
EAT	Exhaust gas Aftertreatment System
LPI	Late Post Injection
WG	Waste Gate
HTCAL	ECU calibration for high exhaust temperature
REFCAL	ECU calibration for normal engine operation
eWG	Electronically controlled waste-gate
BMEP	Brake Mean Effective Pressure