Article citation info:
AOYAGI, Y. Improvement of BSFC and effective NO_x and PM reduction by high EGR rates in heavy duty diesel engine. *Combustion Engines*. 2017, **171**(4), 4-10. DOI: 10.19206/CE-2017-401

Yuzo AOYAGI

CE-2017-401

Improvement of BSFC and effective NO_x and PM reduction by high EGR rates in heavy duty diesel engine

The test engine was a turbocharged 10.5L engine with an intercooler. A performance target was set at a rated power of 300 kW (BMEP = 1.7 MPa) and peak torque of 1842 Nm (BMEP = 2.2 MPa). Emission targets were set at a level of near future and stringent regulation standards in Japan. The engine was equipped with new technologies such as a high pressure common rail system, FCD piston, a high pressure ratio VGT and an aftertreatment system. The high and low pressure loop EGR system was installed and this system with a VGT had a high performance and could increase an EGR rate in order to reduce $BSNO_x$ while maintaining the satisfied BSFC and PM performance simultaneously not only in the steady state condition but also in the transient condition.

Key words: *diesel engine, exhaust emissions, turbocharger, fuel injection*

1. Introduction

Now diesel engines still have considerable advantages in regard to engine power, fuel economy and durability for commercial vehicles when compared with other types of internal combustion engines. These advantages along with the continuous refinement have led diesel vehicles to the widespread use as prime movers for heavy-duty vehicles. At the present time however, a reduction of exhaust emissions such as NO_x, PM and CO_2 is essential, to meet more stringent emission regulations [1], and several breakthrough technologies will be required.

The author's study has aimed at establishing a new combustion concept for clean diesel engines for the new future emission regulations and both wide range and high EGR rates under the high boost pressure, their effects on the engine performance, $BSNO_x$ and PM are discussed.

New A.C.E. Institute Co., Ltd. (New ACE) was established in 1992 and has researched the improvement of thermal efficiency and exhaust emissions in heavy duty diesel engines (HDDE) by single cylinder engines [2–6]. In 2004 New ACE participated the Japanese national project named Super Clean Diesel (SCD) Engine and has added six cylinder engines in its research. In this paper the author has reviewed the research of these 10 years focusing on the improvement of thermal efficiency and exhaust emissions of a heavy duty six cylinder engine [7–9].

2. Clean technologies for diesel engine

A history of Japanese emission standards for heavy duty diesel vehicles is shown in Fig. 1. Japanese emission standards started as a D6 mode in 1974 and changed to a D13 mode in 1994 year. In 2005, a JE05 started as a first transient test cycle. WHTC started as a new Japanese emission regulation from autumn of 2016. A reduction of exhaust emissions is now going by the adoption of new technologies such as turbocharging, intercooling and the common rail fuel injection system, which allows a high pressure injection [10–13]. Further improvement on these technologies will be carried out going forward [2, 4, 5, 7–9]. Catalysts are indispensable for the reduction of exhaust emissions from diesel engines and it is also necessary to minimize engine-out exhaust emissions [12]. Accordingly, it is very important to combine effects of both combustion improvement and aftertreatment systems efficiently [7, 8, 12]. A history of clean diesel technologies for heavy duty engines is shown in Fig. 2.

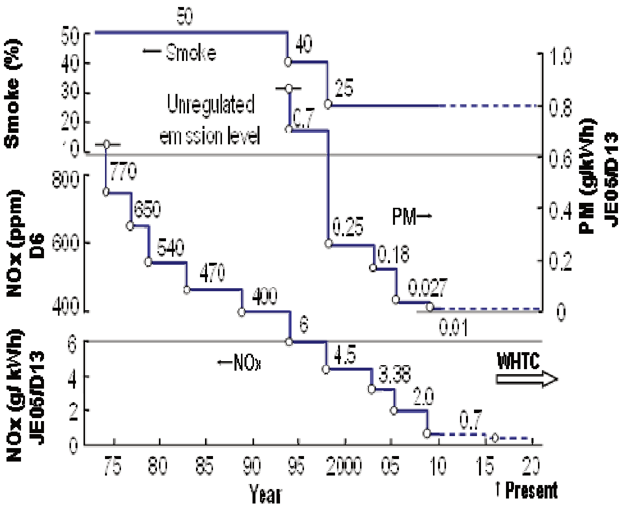


Fig. 1. History of Japanese emission standards for heavy duty diesels

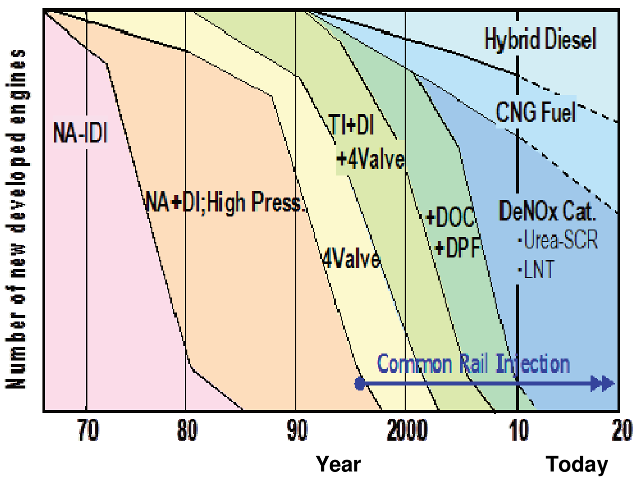


Fig. 2. History of clean emission technologies in heavy duty diesels in Japan

3. Targets of project

The research objectives are low emissions and a high engine performance, and the target emissions are $BSNO_x$ = 0.2 g/kWh and PM = 0.01 g/kWh with aftertreatment systems under the Japanese JE05 transient test cycle. The engine-out emission targets without aftertreatment systems are $BSNO_x$ = 1.0 g/kWh and PM = 0.10 g/kWh under the same test cycle. This target will be achieved by means of combustion improvement and new technologies such as a high pressure common rail system, FCD (Ductile cast iron) piston [10], a high pressure ratio VGT and a combination of high and low pressure loop EGR [7, 8]. After minimizing engine-out exhaust emissions the author will use aftertreatment for the reduction of exhaust emissions from diesel engine [7, 8, 12]. This policy for reduction of exhaust emissions is shown in Fig. 3.

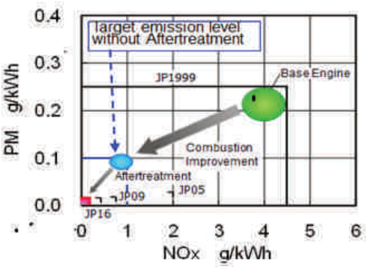


Fig. 3. Strategy of clean emissions

4. Combustion concepts

For the emissions reduction and the high thermal efficiency, many engine components and systems should be improved. Combustion concepts are useful and efficient to develop a brand new engine. The combustion concepts for clean diesel engines have been accomplished and are presented in below. The explanations are as follows;

(1) Lean combustion is necessary for the complete burning, using large quantities of O_2 in a low combustion temperature.

(2) A high boost intake pressure is necessary for combustion in high air density.

(3) A fuel injection in high air density is necessary for reducing exhaust smoke because of a fall of the peak of the fuel/air ratio in a spray.

(4) A high pressure fuel injection is required for a smoke reduction through fine atomization.

(5) A high BMEP engine is needed for a reduction of friction and heat loss.

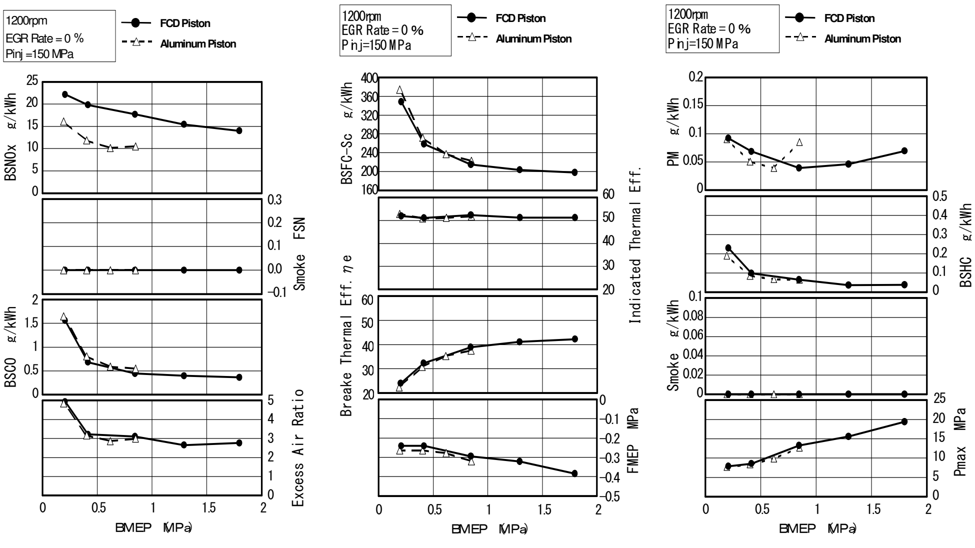
(6) A high EGR rate at a wide speed range and a wide load range is necessary for a drastic $BSNO_x$ reduction.

New technologies are intended for use for the clean diesel engine. Some of these technologies are controlled electronically.

5. New engine and specifications

The author has adopted FCD piston for strength and thermal efficiency instead of aluminum alloy piston and shows the experimental results between FCD piston and aluminum alloy piston by a single cylinder engine before making the six cylinder engine in Fig. 4. Though $BSNO_x$ of FCD is two times of aluminum alloy piston, BSFC of FCD is lower than aluminum alloy because of obtaining high BMEP.

The research engine was modified for high BMEP and a high intake boost pressure from Hino P11C [10]. The engine specifications are presented in Table 1. The newly employed technologies for the engine are shown in Table 2. A schematic of the engine system is illustrated in Fig. 5. A test engine was an in-line six-cylinder turbocharged and intercooled engine with a displacement of 10.5 L, composing of a variable geometry turbocharger (VGT), various cooled EGR systems with a combination of High Pressure Loop EGR (HPL-EGR) and Low Pressure Loop EGR (LPL-EGR), intake-air throttle valves and a back-pressure control valve (BPCV). The VGT is a prototype and had the maximum compressor pressure ratio of 5.0, and this is twice as much as the ordinary turbocharger (approx. 3.0). In Fig. 6 the author shows comparison of compressor map between a current and a high pressure ratio one (SCD).



a. Emissions b. BSFC and FMEP c. PM, BSHC and Smoke

Fig. 4. The comparison of FCD piston and Aluminum alloy piston in combustion characteristics

Table 1. Specifications and targets of clean diesel engine

Engine Type		DI, In-Line 6
Bore × Stroke		Φ 122 mm × 150 mm
Displacement		10,520 cm^3
Compression Ratio		15.3
Swirl Ratio		1.0–9.0
Injection Nozzle		Φ 0.139 mm × 8-155°
Max Output	Engine Speed	2000 rpm
	Output	298{405} kW {PS}
	BMEP	1.7 MPa
Max Torque	Engine Speed	1400 rpm
	Output	1842{188} Nm {kg m}
	BMEP	2.2 MPa

Table 2. Technologies for clean emissions

No.	New technologies
1	High boosting SCD Turbocharger
2	FCD piston & strong structure engine
3	200 MPa common rail injection system
4	High & low combined pressure loop EGR
5	EGR valve and intake air valve
6	High efficiency EGR cooler
7	Variable Valve Actuation
8	Variable Swirl system
9	Efficient SCD after-treatment
10	SCD Electronic control system for JE05

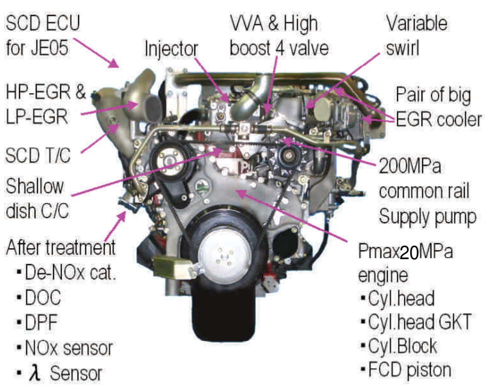


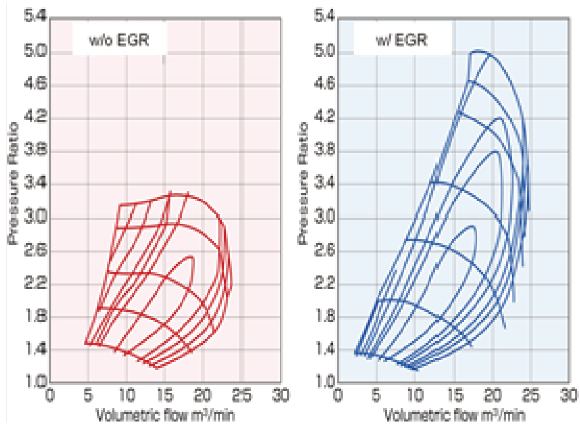
Fig. 5. New engine for clean emissions and its new technologies

As aftertreatment systems, a Lean-NOx Trap (LNT+ DOC) was used for reducing BSNOx and a catalyzed DPF was used for reducing PM from exhaust gases. In Japan low sulfur diesel fuels with the standard sulfur content of less than 10 ppm were used as test fuels, and today they are commercially available. Actual test fuels were the 7 ppm sulfur content. Furthermore, low sulfur engine oil containing 0.26 mass% of sulfur was used as lubricant oil.

6. Experimental measurement for HDDE

An engine performance was measured using a dynamometer system with data acquisition and control systems (FAMS-8000 series; Ono Sokki Co. Ltd.). Exhaust emissions were measured using an emissions analyzer (MEXA-7100DEGR; Horiba Instruments Ltd.).

Smoke was measured using smoke meters (Tsukasa Sokken Co. Ltd. and AVL Co., Ltd.) during the steady state test. An AVL opacimeter was used to measure smoke in the transient test. Particulate matter (PM) was measured using a micro-tunnel (DLT-1303; Horiba Ltd.). An intake air flow rate was measured by a laminar flowmeter (Tsukasa Sokken Co. Ltd.). Cylinder pressure sensing was performed using a pressure transducer (Type 6043A; Kistler Instruments AG). A combustion analysis for the rate of heat release and others was performed using an analyzer (DS-2000 series; Ono Sokki Co. Ltd.).



a. Current Comp. Map b. SCD Comp. Map

Fig. 6. Comp. map comparison of current and new VGT/C

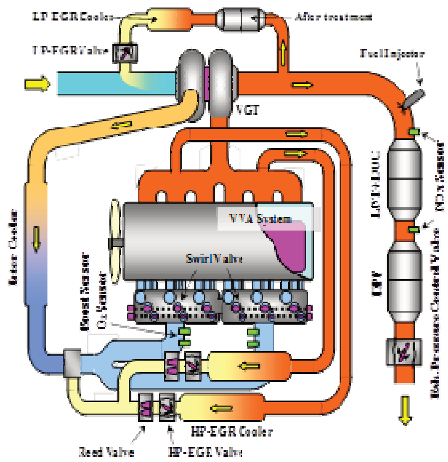


Fig. 7. Layout of new engine for clean emissions

7. Experimental result

7.1. Definition of EGR rate

The EGR rate is defined as shown below:

$$\text{EGR Rate} = \frac{[CO_2]\text{in} - [CO_2]\text{atm}}{[CO_2]\text{exh} - [CO_2]\text{atm}} \times 100\,\%$$

$[CO_2]$ signifies the CO_2 concentration. CO_2 concentrations were measured by an emission analyzer at each point: $[CO_2]$in was measured at the intake manifold inlet; $[CO_2]$exh was measured at the exhaust outlet of a turbocharger; and $[CO_2]$atm was measured in the test room. The $[CO_2]$atm value of 0.04% was used as the atmospheric CO_2 concentration.

7.2. Effects of HPL and LPL-EGR on turbocharging

Fig. 8a shows an intake fresh air flow rate Ga without EGR gas, a boost pressure Pb, a turbocharger (T/C) speed and an exhaust gas flow rate Gt from top in changing total EGR rates. In this case, EGR rates were changed at fixed VGT nozzle closing. Though the EGR rate was the same value, a HPI (High Pressure Index) was varied. A fraction of HPL-EGR in the combination of HPL-EGR and LPL-EGR is designated as a HPL-EGR index and is represented as HPI (%) shown in the definition in the previous section. The EGR rates were compared in four conditions: HPI = 0%, 40%, 60% and 100%, which are marked with ▲,●,◆ and ■ without a back pressure control valve (BPCV) and △,○ and ◇ with a BPCV respectively to increase the EGR rate. HPI = 100% means using HPL-EGR only, whereas HPI = 0% denotes the use of LP-EGR only. This HP-EGR index is defined by the following equation

$$\mathrm{HPI}\ \% = \frac{\text{HP-EGR Rate}}{\text{HP-EGR Rate + LP-EGR Rate}} \times\ 100\ \ \%$$

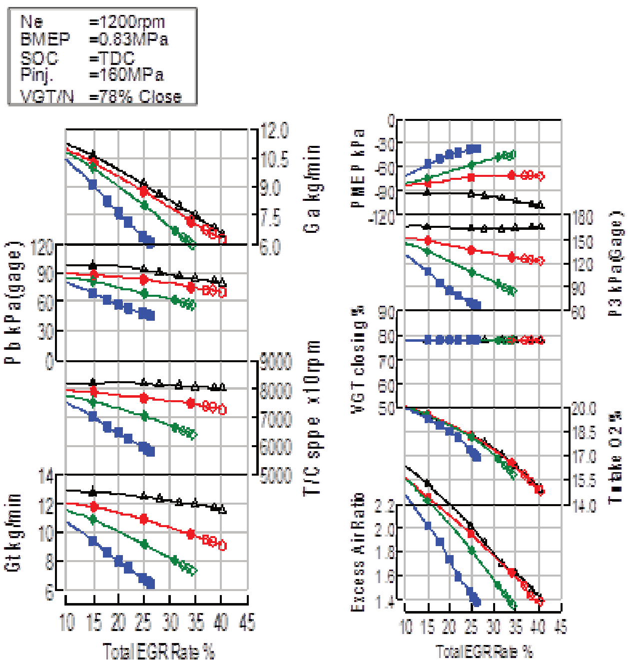
Test conditions were an engine speed at 1,200 rpm, a 40% load (BMEP = 0.83 MPa), a fuel injection pressure at 160 MPa, fuel ignition timing at TDC and VGT nozzle closing fixed at 78%. This is the condition which is frequently used in the JE05 Japanese transient test cycle.

In case of HPI=100% (HPL-EGR only), the EGR rate was limited to 26% and the Gt of HPL-EGR rapidly decreased to EGR rate 26%. On the contrary, in case of the combination of HPL-EGR and LPL-EGR with the BPCV, the EGR rate (HPI = 60, 30, 0%) increased to 40% and the Gt of the combination of HPL-EGR and LPL-EGR gradually decreased to EGR rate 40%. This reason is as follows; In case of LPL-EGR, the Gt to the turbine was the same quantity when the EGR rate increased. On the contrary, in case of HP-EGR, the Gt to the turbine was lower quantity when the EGR rate increased, and the Ga and Pb rapidly went down.

Fig. 8b shows a pumping mean effective pressure (PMEP), a pressure before the turbine operation (P3), VGT nozzle closing, an intake O_2 concentration and an excess air ratio from top. Conditions were the same as Fig. 8a. The values of the P3, intake O_2 and the excess air ratio had the same tendency shown as Fig. 8a when the EGR rate increased. However, the PMEP had a different tendency when the EGR rate increased. When the EGR rate increased, the PMEP of LPL-EGR increased. On the contrary, the PMEP of HPL-EGR decreased when the EGR rate increased. This means that the BSFC in LPL-EGR might be deteriorated.

7.3. Effect on BSFC by EGR

Fig. 9 represents $BSNO_x$, smoke, and brake specific fuel consumption (BSFC) from top at fixed VGT nozzle closing with a various EGR rates. Test conditions were the same as before. These results were compared with the same smoke level of FSN = 0.5. $BSNO_x$ was reduced by approximate 50% ($BSNO_x$ from 2.0 g/kWh to 1.0 g/kWh) compared with the case of HPL-EGR only. The BSFC in LPL-EGR increased when the total EGR rate increased. On the other hands, in case of HPI = 60% (green line) in the combination of HPL-EGR and LPL-EGR, the BSFC was able to be improved in comparison with HPL-EGR only (blue line) without smoke deterioration.



a. Ga: intake air quantity, Pb, T/C speed, Gt: Gas quantity,

b. PMEP, P3, VGT nozzle closing, intake O_2 and excess air ratio

Fig. 8. Experimental results of HPL-EGR and LPL-EGR in changing the total EGR rate

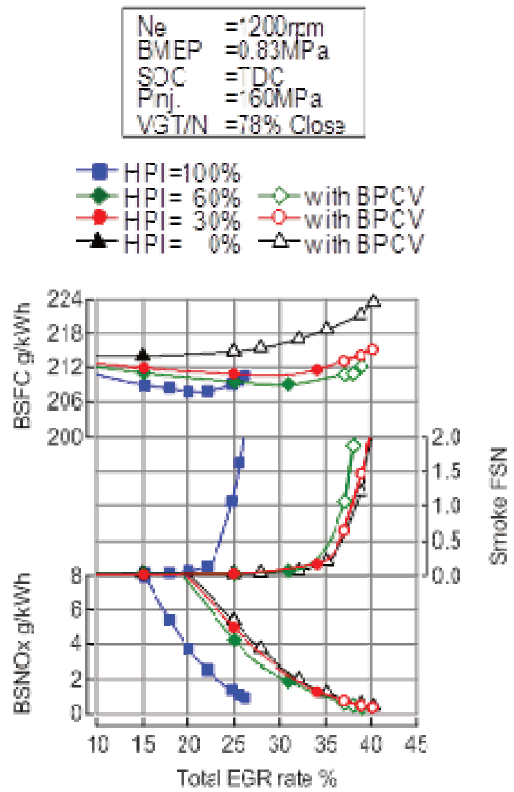


Fig. 9. Experimental results of BSFC, Smoke and $BSNO_x$ in changing the total EGR rate

7.4. Operation lines with EGR

Fig. 10 represents operating lines on the compressor map of the high pressure ratio turbocharger with EGR (red line) and without EGR (black line) when changing the load from 20% to 100% (BMEP 0.44 to 2.2 MPa) at an engine speed 1200 rpm. With the 20% load, the EGR rate was 44%, and this value is relatively high. With the 100% load the EGR rate decreased to 24% when the load ascended to 100%, and the HPL-EGR index was approx. 50% with a combination of HPL-EGR and LPL-EGR. It is noteworthy that the operating line without EGR moved from the center of the map to the surge line side when the EGR rate increased. It must be considered that the operating line of the high EGR rate approach to surge lines as the EGR rate increases, and it is necessary to develop countermeasures of this phenomenon.

Fig. 11 shows the operating lines in the full load condition with EGR at the engine speed from 800rpm to 2,000 rpm. At 800 rpm, the EGR rate was 23% with HPI = 16%, and at 2000 rpm, the EGR rate was 15% with HPI = 43%. At the low engine speed, the EGR rate was high and the value of HPI was 10%, which is relatively low because of small air quantities. As the engine speed increased, the EGR rate became lower such as 15% at 2000 rpm and the value of HPI was 42%, which is relatively high because of large air quantities. It is important to increase the EGR rate at the high engine speed in order to reduce $BSNO_x$ emissions.

7.5. Result of transient test cycle

In Japan, the JE05 transient test cycle has been used for emission standards since 2005 to 2016 autumn. Fig. 12 shows the results under the JE05 transient test cycle. Orange lines represent the results with original engine specifications, which are before the transient cycle tuning test, and black lines represent with improved engine specifications, which are after the transient cycle tuning test. The peaks of opacity and $BSNO_x$ were eliminated by observing the results of transient test cycle. It is improved gradually by HPL-EGR and LPL-EGR incorporated with improvements on the VGT-response, injection-timing, valve-timing and etc.

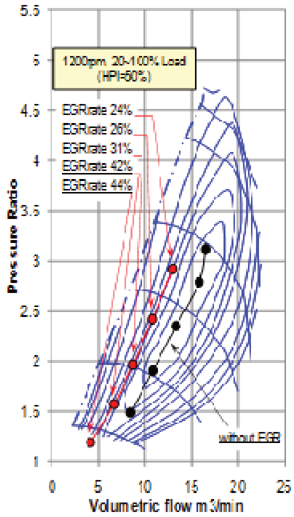


Fig. 10. Operating lines with and without EGR on the compressor map in changing loads at 1200 rpm

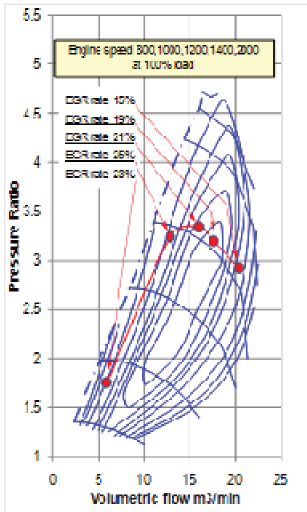


Fig. 11. Operating lines with EGR on the compressor map in changing the engine speed with 100% load

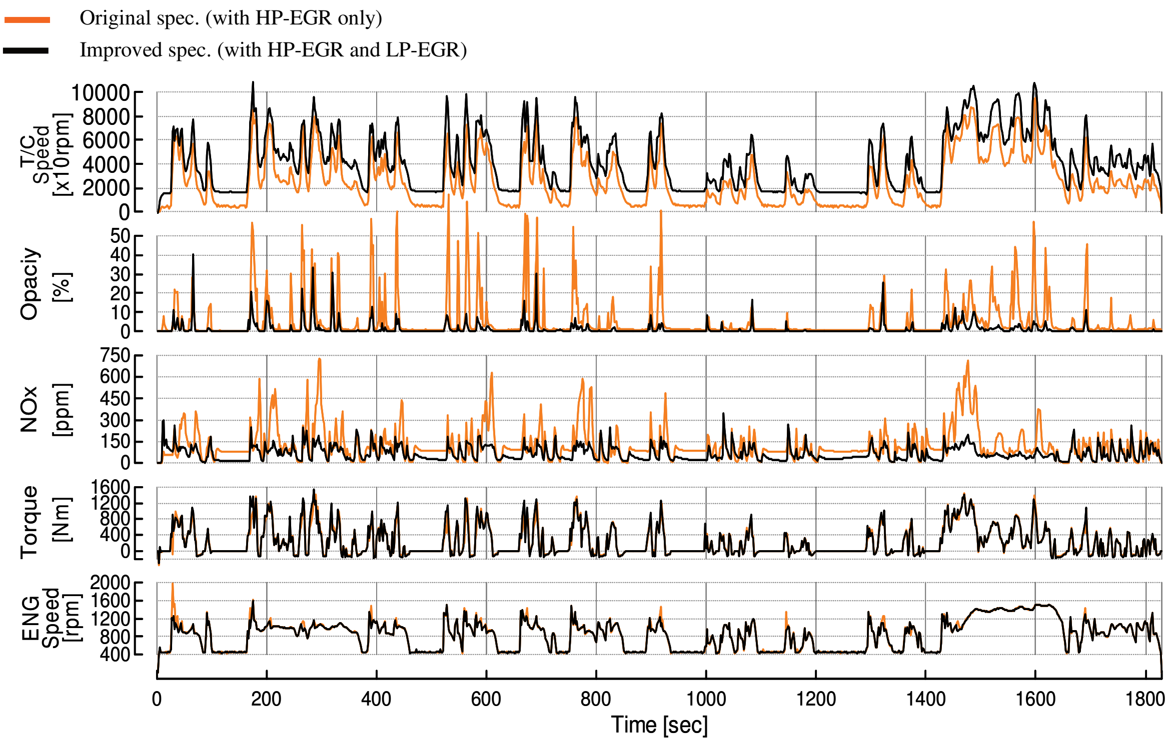


Fig. 12. Experimental results under JE05 transient test cycle in comparison between the original engine specs. and the improved engine specs

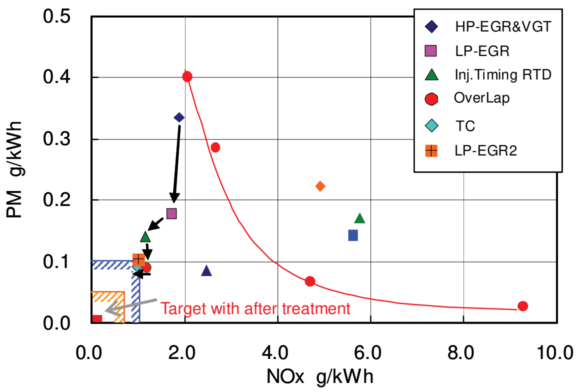


Fig. 13. Final experimental emission results from the original engine by transient test cycle

Fig. 13 represents a summary of the results under the JE05 transient test cycle showing $BSNO_x$ and PM trade-off relations. When boosting with a VGT, HPL-EGR and LPL-EGR and engine-out exhaust emissions were reduced to the effective range of after-treatment systems. The curved red line in Fig. 13 shows a trade-off by changing the HPL-EGR valve positions: 5%, 10%, and 15% before the turning test. After the turning test, approx. 47% of PM, 10% of $BSNO_x$ and 1.4% of BSFC were reduced by the combination of HPL-EGR and LPL-EGR comparing with the HPL-EGR only.

Finally, this engine satisfied the emission targets; $BSNO_x$ = 0.2 g/kWh and PM=0.01 g/kWh with the after-treatment systems, which include a LNT, a DOC and a DPF. Thus, this engine has achieved the emission targets by employing advanced technologies for the reduction of exhaust emissions.

8. Conclusion

The author at New ACE has studied the enhancement of the engine performance and the reduction of exhaust emissions by inducting substantial air into the cylinder with high EGR rates for the high boosted and intercooled diesel engine. As a result of the experiments, the following facts were derived:

- FCD piston combined with high rate EGR gives good exhaust emissions and improved thermal efficiency.
- The high boost pressure VGT (pressure ratio 5) with high EGR rates under the condition of a high injection pressure caused no significant degradation of the performance but yielded a high thermal efficiency.
- By using the high EGR rates, the $BSNO_x$ reached a lower emission level than without EGR and no increase of smoke and PM was observed at this experiment.
- The combined EGR system of HPL-EGR and LPL-EGR used for this study had a high performance, which increases the EGR rate while maintaining BSFC and the boost pressure, and decreased $BSNO_x$ and PM simultaneously not only in the steady state condition but also in the transient condition.

Acknowledgment

This research was done under the auspices of the annual research fund of New A.C.E. Institute Co., Ltd. and the project to promote Research and Development of Next-generation Environmentally Friendly Heavy Duty Vehicles of the Ministry of Land, Infrastructure, Transport and Tourism, to which we are grateful.

Nomenclature

BMEP brakes mean effective pressure, MPa
BSFC brake specific fuel consumption, g/kWh
BSNOx brake specific NOx, g/kWh
FSN filter smoke number, -
Ga air flow rate without EGR gas, kg/min
Gt exhaust gas flow rate, kg/min
Ne engine speed, rpm
Pb boost pressure, kPa (gauge)
Pinj fuel injection pressure, MPa
PM particulate matter, g/kWh
PMEP pumping mean effective pressure, MPa
Smoke smoke, %
T/C speed turbocharger rotation speed, ×10 rpm
BPCV back pressure control valve
[CO2]atm CO_2 concentration in atmosphere, %
[CO2]exh CO_2 concentration in exhaust gases, %
[CO2]in CO_2 concentration in intake gases, %
DOC diesel oxidation catalyst
DPF diesel particulate filter
LNT lean NO_x trap
HPL-EGR high pressure loop EGR
LPL-EGR low pressure loop EGR
HPI HPL-EGR rate in total EGR rate
JE05 heavy duty diesel transient test cycle in Japan
VGT variable geometry turbocharger

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Yuzo Aoyagi, DEng. – Counsel, New A.C.E. Institute Co., Ltd. and Temporal Lecturer of Okayama University, Japan.

e-mail: *Aoyagiyz1@jcom.zaq.ne.jp*