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Increasing low-load exhaust temperatures to aftertreatment suitable levels on a two-stroke EMD 645

Emission Reduction Technologies - Engine Measures & Combustion Development

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ABSTRACT

Throughout the world, medium-speed two-stroke diesel engines are used largely in rail, intra-coastal marine, and power generation applications. These engines, while reliable, have significant issues when it comes to criteria pollutants such as oxides of nitrogen (NOx) and particulate matter (PM). As regulations are tightened, these older engines will need to be replaced with newer Tier 4 engines at great expense to the end user or updated to meet stricter emissions requirements. However, the update pathway is difficult due to their low exhaust temperatures which makes employing aftertreatment systems difficult.

This paper investigates options to increase the exhaust temperatures to a level where selective catalytic reduction (SCR) based aftertreatment would be a viable solution for reducing emissions, without negatively impacting fuel efficiency. Testing was carried out on a roots-blown, mechanically injected, two-stroke EMD 16-645E engine. As equipped, the roots blower produces air-fuel ratios (AFR) at Idle as high as 350:1 which leads to very low engine out exhaust temperatures.

Various options to increase exhaust temperature were investigated, including cylinder deactivation, exhaust valve deactivation, and boost air pressure reduction (simulating an electrically driven roots blower). This paper covers the design, test process, and experimental results of the initial investigation and shows that exhaust temperatures required for SCR aftertreatment are achievable on engines of this type.

1 INTRODUCTION

Forced induction uniflow two-stroke diesel engines (EMD 645 and 710) are designed to operate at best efficiency at or near their highest power output. Delivery of compressed air from either a Roots blower or a turbocharger is tailored towards this high-load, high-speed portion of the operating envelope. However, gas exchange at lower throttle notches[1] provides so much airflow that exhaust temperatures are too low for efficient aftertreatment performance over much of the duty cycle, and the pumping work associated with excess scavenging air significantly worsens fuel economy.

Increasing engine-out exhaust temperature at idle and at lower speed and lighter load conditions will facilitate efficient exhaust aftertreatment and minimize the unnecessary scavenging air flow that negatively impacts exhaust emissions and fuel economy.

Figure 1 shows the engine-out exhaust temperature on a 2.25 MW two-stroke EMD 12-710 engine over a US EPA Federal Test Procedure (FTP) locomotive exhaust emissions certification test. Temperatures below Notch 5 are below 260°C, a typical target “light-off” temperature needed for adequate NOx conversion in a selective catalytic reduction (SCR) system. Consequently, operating conditions for ~73% of the US-EPA line haul duty cycle and ~93% of the US EPA switch duty cycle do not produce sufficiently high exhaust temperatures to allow an SCR aftertreatment system to be effective at reducing NOx emissions. Oxidation of hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM) using a catalyzed diesel particulate filter (DPF) also require minimum exhaust temperatures in the range of 260°C to begin to be effective.

This paper describes one proposed approach to increasing exhaust temperature at idle and lower notches using an exhaust valve deactivation (EVD) system, allowing selected cylinders to operate at higher load while the deactivated cylinders operate as air springs. Simultaneously the speed of the Roots blower or turbo-supercharger is controlled to optimize air/fuel ratio. This process will rotate the operating cylinders around the engine, and fuel may or may not be injected into the air spring cylinders. Idle, for example, may be achievable with only two active cylinders operating in a 12- or 16-cylinder engine, elevating temperatures in-cylinder and in the exhaust, and the remaining cylinders in air spring mode.

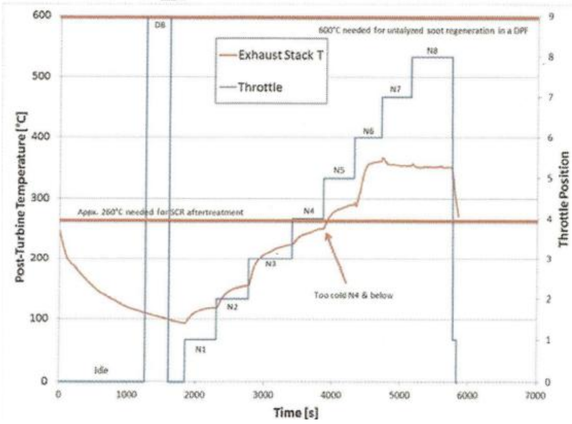

Figure 1. EMD Exhaust Temperatures by Throttle Position

2 APPROACH

In the U.S., locomotives manufactured after 1972 are required to meet exhaust emission regulations specified by the U.S. Environmental Protection Agency (EPA). These locomotive regulations began in 2000, and applied to older locomotives at time of overhaul. The period between 2002 and 2014 implemented progressively cleaner standards for new locomotives, cumulating in “Tier 4” regulations for new locomotives that started in 2015. While locomotives that were originally manufactured before 2015 are not required to meet Tier 4, there is mounting pressure for the installed locomotive fleet to keep pace with the emission improvements of other mobile emission sources. The fleet of existing EMD two-stroke engines exceeds 72,000 worldwide, many of which are in railroad operation in the US (powering some 40% of the existing locomotive fleet). While these engines are also very popular for inland marine and stationary power generation applications, the majority are used in locomotive applications. At this time, these EMD engines can only take advantage of an SCR aftertreatment system in some marine and stationary power applications with a highly loaded duty cycle. The balance of the EMD engines are not capable of meeting Tier 4 emissions levels because an SCR system would not be activated over enough of the duty cycle.

As an example of the potential impact of cleaning up the legacy locomotive fleet, estimated annual diesel fuel consumption for line-haul locomotive activity in southern California ports is almost four

[1] Throttle Notches in locomotives are pre-set engine speed and load conditions. In North America, generally there are 8 Throttle Notches available to the operator, with Notch 1 being the lowest traction power, and Notch 8 being maximum traction power.

million gallons, and NOx emissions of 659 tonnes[1]. Enabling SCR aftertreatment deployment on the legacy locomotive fleet through the use of the combination of EVD and airflow management could result in roughly half of the on-port locomotive fleet now being able to comply with EPA Tier 4 emissions, reducing NOx emissions by approximately 40% overall. Initial testing indicates that EPA line-haul, duty-cycle weighted fuel consumption may be reduced at least 1%, equal to more than 200 tonnes of CO_2e annually.

2.1 Exhaust Valve Deactivation Mechanism

An isometric view of the proposed EVD system (shown applied to only two cylinders of an EMD 16-710 locomotive engine) is shown in Figure 2. Current EMD two-stroke engines use camshaft segments for three or four cylinders, fastened together with connecting spools. These existing multi-cylinder camshafts would be replaced with single-cylinder segments occupying the same space. The exhaust lobes would be engaged and disengaged electronically on a cylinder-by-cylinder basis. Other valve deactivation systems have been used in automotive applications, although the valvetrain geometries are different from the EMD engine, necessitating a different design.

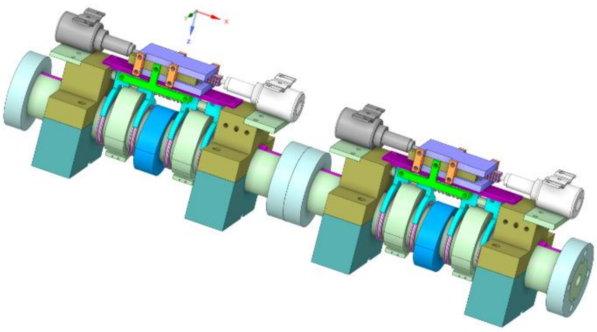

Figure 2. Exhaust Valve Deactivation Hardware Design for EMD Two-Stroke Engines

2.2 AFR Control

The EMD 16-645E engine is equipped with two mechanically driven Roots blowers, with each one feeding the left and right bank air manifolds. However, the engine block on both the EMD 645 and EMD 710 series engines allows for boost air to flow from one bank to the other, meaning on this engine a Roots blower could be removed while still providing air to all 16 cylinders.

To simulate an electrically driven blower or variable speed turbocharger instead of the traditional EMD turbosupercharger, adjustments were made during the course of testing including removing one of the two blowers as well as additional reduction in boost air pressure through multiple gate valves allowing for controllable leakage from the boost air manifold.

2.3 Test Equipment

2.3.1 Emissions Measurements

Raw gaseous emissions were sampled continuously from within the exhaust. A heated line was used to transfer the raw exhaust sample to the emission instruments for analysis. Measured gaseous emission concentrations included hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), oxides of nitrogen (NO, NO_x), and methane (CH_4).

Total hydrocarbon concentration in the raw exhaust was determined using a Horiba heated flame ionization detector (HFID), calibrated on propane. NO_X concentration in the raw exhaust was measured with a heated chemiluminescent detector (HCLD). NO_X correction factors for ambient air humidity were applied as specified by EPA in 40CFR1065. Concentrations of CO and CO_2 in the raw exhaust were determined by non-dispersive infrared (NDIR) instruments, and O_2 concentrations were measured using a magneto-pneumatic analyzer. Raw exhaust CH_4 concentration was measured using a non-methane cutter (NMC) and a dedicated heated flame ionization detector (NMC-HFID) as outlined in 40CFR1065.365(d).

Gaseous mass emission rates were computed via chemical balance of fuel, intake air, and exhaust gas using the procedures specified in 40 CFR Part 1065.

2.3.2 Fuel Flow Measurements

Diesel fuel consumption was measured on a mass basis. The mass measuring device used by SwRI is a Micro Motion® CMF-25. Before testing, the Micro-Motion calibration was verified and compared to a calibrated scale. The Micro-Motion measures the makeup fuel supplied to a closed loop system, which is kept at a constant pressure that supplies fuel to the locomotive lift pump.

The SwRI fuel cart is equipped with heat exchangers and a chilled water system to regulate the fuel supply temperature to the locomotive at a target of 27°C (±6°C). The fuel supply temperature is measured at the outlet of the fuel cart, just after the heat exchanger.

2.3.3 Power Measurements

Traction power was measured on the DC bus within the locomotive. Voltage was measured directly and current was measured using a DaniSense DS5000 current transformer. The output of the DaniSense current transformers and direct voltage measurement was sent to a Yokogawa WT3000E power analyzer.

Cooling fan power was measured using a pair of current transducers, direct voltage measurements, and the Yokogawa WT3000E Power Analyzer. Mechanical loads such as air compressor and traction motor blower loads were calculated using OEM published calculations.

Gross power was calculated using published alternator efficiencies for this locomotive type.

3 TESTING RESULTS

3.1 Initial Emissions and Engine Health Check

To verify engine health, an emissions test was run on the engine prior to any cylinder deactivation or AFR studies were conducted. The engine was in an EPA Tier 0+ configuration for this testing. The following tables show the emissions test results and the applicable EPA standards. Note that EPA line-haul-cycle-weighted results and standards are shown for reference as they are not applicable to this engine based on it's rated power output. Also note that PM is regulated by EPA, but was not measured for these screening tests.

The engine met Tier 0 standards for gaseous emissions and was deemed healthy and representative for further investigations.

Table 1. EPA Duty Cycle Weighted Emissions

	EPA Switch Duty Cycle (all engines)			
	BSFC [g/kW-hr]	BSHC [g/kW-hr]	BSCO [g/kW-hr]	BSNOx [g/kW-hr]
Test Engine	293.8	0.94	2.3	17.6
T0 EPA Standards	*NS*	*2.82*	*10.7*	*18.8*

	EPA Linehaul Duty Cycle (>2.2MW only)			
	BSFC [g/kW-hr]	BSHC [g/kW-hr]	BSCO [g/kW-hr]	BSNOx [g/kW-hr]
Test Engine	264.6	0.54	3.1	17.8
T0 EPA Standards	*NS*	*2.8*	*10.7*	*18.8*

3.2 Valve Deactivation Hardware Testing

To verify the prototype hardware functioned as expected, the exhaust valve deactivation hardware was first tested on a single cylinder in a multi-cylinder EMD 16-710 engine. This initial testing was used to both vet the hardware and to test concepts for increasing exhaust temperature to appropriate levels.

As the AFR on these engines is sufficiently high (330:1 at idle), testing looked at the ability and effects of multiple injection events on a single air charge. After the initial combustion event, the exhaust valves were deactivated for two additional cycles. This showed a large increase in exhaust port temperatures at Idle as shown in Figure 3.

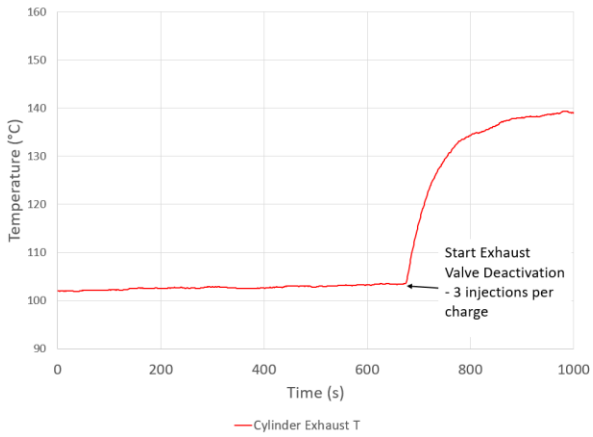

Figure 3. Idle Exhaust Port Temperature Using Exhaust Valve Deactivation

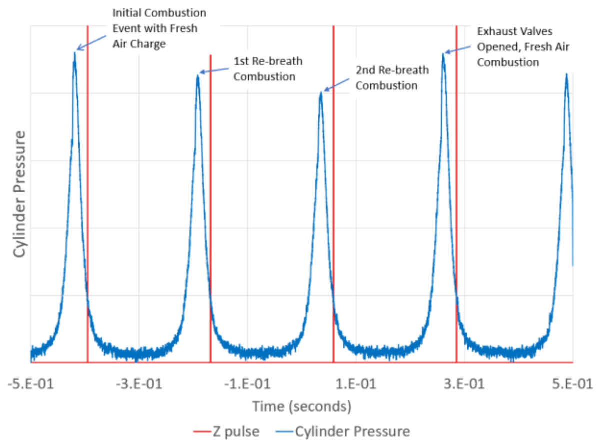

Figure 4. Changes in Cylinder Pressure Using Multiple Injections per Charge

While the temperature increase was an overall positive using this injection strategy, combustion quality was affected. Cylinder pressure traces showed a 5-6% reduction in peak cylinder pressure with each subsequent combustion event, indicating changes in combustion phasing/quality.

Due to hardware availability at this stage, full engine testing of this combustion strategy has not been completed at this time, so its effect on full engine performance is not known at this time. A prototype EVD system was developed and tested on one cylinder of a 16-710 two-stoke engine. From here, the focus shifted to the role of AFR management, which is discussed in the next Section.

3.3 Test Configurations

Full engine testing was completed on an EMD 16-645 engine using multiple test configurations. The test configurations were chosen to determine the impact on emissions, fuel consumption, and exhaust temperature changes with changes in AFR and the number of active cylinders. The configurations that were tested are listed in Table 2. The Air Fuel Ratios (AFR) tested are shown in Figure 5.

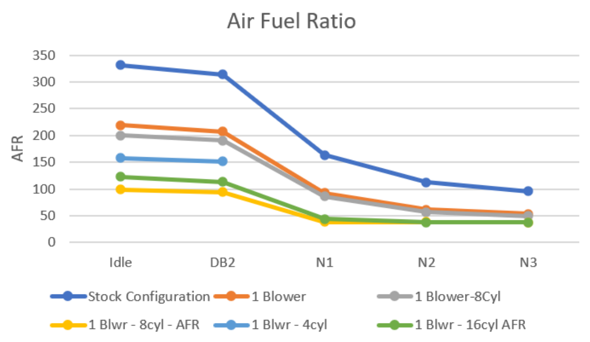

Figure 5. Air Fuel Ratios Tested at Each Test Condition

Table 2. Test Configurations

Configuration	# of Blowers	# of Cylinders	Fuel Injection Timing Setpoint
1	2	16	TDC
2	1	16	TDC
3	1	8	TDC
4	1	4	TDC
5	1	4	4°ATDC

Note that while mechanical injection timing is set at a common point, there are timing variations built into the injector helices which change with rack position (fuel volume).

While this proof-of-concept testing was completed on a mechanically controlled injection system, it is expected that electronic injection will be used in any production version.

3.4 Throttle Notches

Diesel-electric locomotives in North America use discrete throttle positions that command specific engine speeds and power outputs. While many newer locomotive control systems regulate power output to a specific brake power, older locomotives such as the locomotive tested in this program regulate power to a specific tractive power. This means that at any given throttle position, engine brake power can vary with variations in vehicle accessory loads.

With that, Table 3 shows the nominal engine speed and load points for each throttle position tested.

Throttle Notch	Speed (rpm)	Brake Power (kW)
Idle	321	13
DB2	385	14
Notch 1	321	105
Notch 2	385	215
Notch 3	517	340

3.5 Cylinder Deactivation Testing

During full engine testing, the rocker arms were removed from inactive cylinders, simulating a full valve deactivation system and the injectors were mechanically disconnected from the rack.

For the AFR runs, additional boost leaks were induced using various gate valves attached to the intake air manifold. These were used to simulate a decoupling of the compressor from the engine, replacing the mechanically driven blowers with an electrically controlled blower.

3.5.1 Exhaust Temperatures

The overall goal of this project was to determine if exhaust temperatures on these legacy engines could be increased to temperatures that were viable for aftertreatment systems. For most SCR systems, that target temperature is 260°C to hit NOx conversions of >50%.

Figure 6 shows the target temperatures were able to be achieved at all loaded throttle positions. With eight active cylinders and lower AFR, sufficient exhaust temperatures were achieved at N1-N3, while sufficiently high exhaust temperatures were achieved using all 16 cylinders starting at Notch 3, again with reduced boost air pressure.

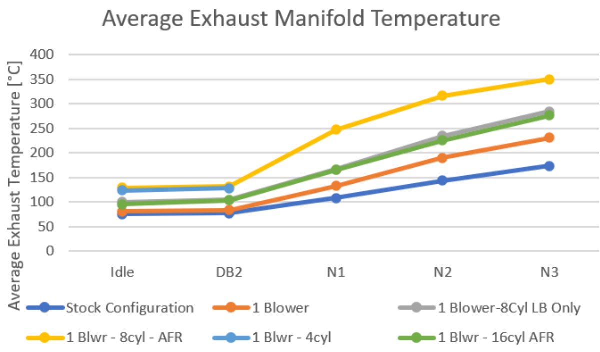

Figure 6. Exhaust Temperatures at Various Engine Configurations

Additional points were run to better understand the trends associated with AFR and the number of active cylinders. Figure 7 indicates that both variables have a significant impact on exhaust temperatures, but that at a given AFR a reduction in the number of active cylinders has a large impact on exhaust manifold temperatures.

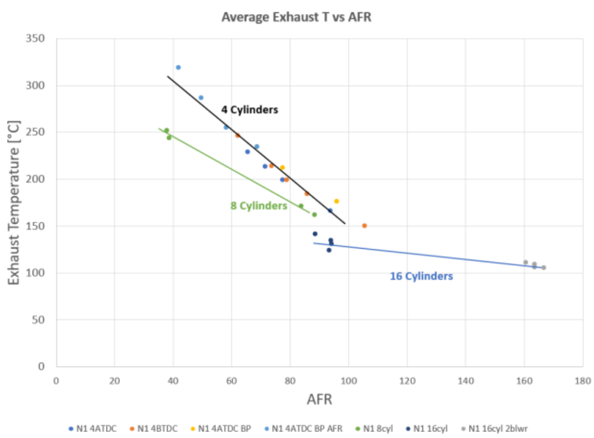

Figure 7. Exhaust Temperatures Trends With Number of Active Cylinders at Notch 1.

3.5.2 Fuel Consumption

While upgrading these legacy engines to cleaner emissions standards is important from a criteria pollutant perspective, it is also important not to increase the associated greenhouse gas emissions in the process. This initial testing showed that reductions in fuel consumption at the unloaded throttle positions were possible, while equivalent brake specific fuel consumption values were feasible at loaded throttle positions (Figure 8).

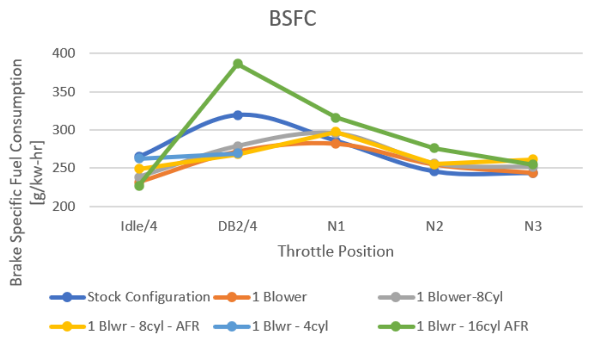

Figure 8. BSFC Trends

Note that with the mechanical engine control system on the test engine, there were severe limitations on control of injection timing and duration. It is believed that with the reduction in pumping losses from the deactivated cylinders, an electrical injection control system would be capable of reductions in fuel consumption while still achieving the necessary exhaust temperatures.

3.5.3 Engine Out Emissions

With sufficient temperatures, a DOC/SCR aftertreatment system is capable of significant reductions in exhaust emissions. Carbon Monoxide (CO) and hydrocarbons (HC) are oxidized by the DOC, and NOx is converted to NO_2 and reacted with urea on the SCR catalysts. Engine out emissions still give insight into the combustion and engine performance.

All points run saw HC emissions at or lower than the engine baseline. Reductions in the number of active cylinders showed greater than 50% reductions from the baseline (Figure 9).

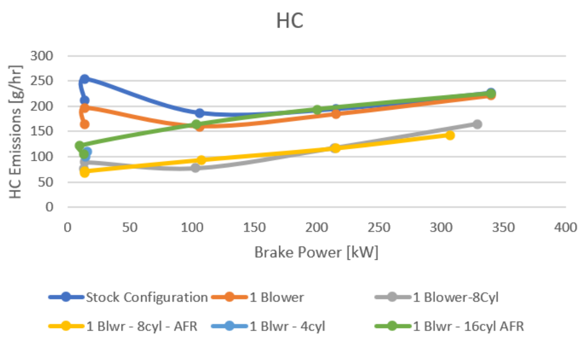

Figure 9. Engine Out HC Emissions

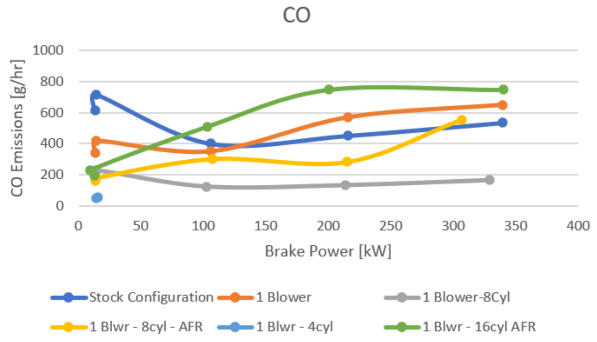

Figure 10. Engine Out CO Emissions

Carbon Monoxide emissions did not show the same trend as HC (Figure 10). While HC emissions on these legacy engines are largely influenced by engine oil, CO emissions are a result of the combustion of the fuel.

The unloaded throttle positions showed large decreases in CO emissions, but the loaded throttle positions showed both large increases and large decreases in CO. The largest increases were seen when running all 16 cylinders with one blower disabled and the AFR further reduced.

CO emissions with reductions in the number of active cylinders showed decreases or near equivalent engine out emissions. This is another area where electronic control of the fuel injection timing would play a large part, as timing advances would allow for more efficient combustion, reducing CO emissions and BSFC, while increasing NOx emissions. CO emissions will be readily mitigated with the presence of a DOC and increased exhaust temperatures.

These engines are significantly higher on NOx than a US EPA Tier 4 engine, but with SCR aftertreatment increases in NOx emissions are generally not an issue. Ideally, engine performance gains could be had by increasing engine out NOx while keeping tailpipe NOx emissions low through the SCR.

This testing showed that reducing the AFR with all 16 cylinders operating actually gave large engine out NOx reductions, while reductions in the number of active cylinders increased NOx at higher engine power outputs (Figure 11). As with the 16 cylinder testing, reductions in AFR showed equivalent decreases in engine out NOx emissions.

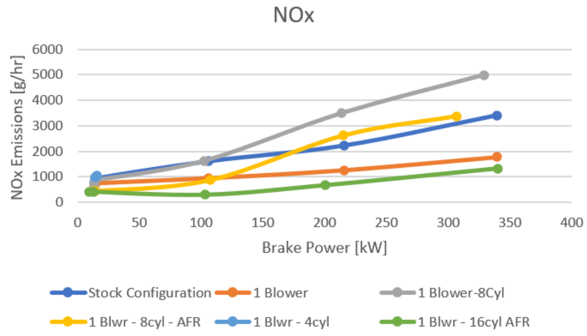

Figure 11. Engine Out NOx Emissions

4 CONCLUSIONS

The purpose of this testing was to demonstrate the functionality of a prototype exhaust valve deactivation system for EMD 2-stroke engines, and the impact of AFR control to determine if such a system could help achieve sufficient exhaust for a DOC/SCR aftertreatment system.

Testing showed that the EVD system worked and allowed for multiple injection events on a single air charge as well as full cylinder deactivation if an alternate engine control system with electronic fuel injection was installed.

With cylinder deactivation enabled, significant increases in exhaust temperature were seen. Exhaust temperatures at the levels necessary for DOC + SCR aftertreatment systems were achieved at all loaded throttle positions with minimal impacts on BSFC.

While further development is needed, the cost of cleaning up these legacy engines will be far less than the cost of replacing them with new engines at current EPA/IMO levels, giving end users more options as regulations reduce or remove the ability to utilize legacy engines that are currently in use around the world.

5 DEFINITIONS, ACRONYMS, ABBREVIATIONS

AFR – Air/Fuel Ratio

BSFC – brake-specific fuel consumption

DOC – diesel oxidation catalyst

EMD – Electro-Motive Diesel

EPA – U.S. Environmental Protection Agency

EVD – exhaust valve deactivation

OEM – original equipment manufacturer

SCR – selective catalytic reduction

6 REFERENCES AND BIBLIOGRAPHY

[1] Port of Los Angeles: Inventory of Air Emissions for Calendar Year 2023

7 CONTACT

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