Ultralow NO_x during Low-loads and Idle

Previous technical papers outlined the ability of the Achates Power opposed-piston (OP) engine to meet the 2027 Ultralow NO_x regulation for heavy-duty trucks from the California Air Resources Board (CARB) (HD Diesel Performance Results - 2020) and provided a summary of a program review of the Heavy-Duty Diesel Demonstration Program, updating the technical results (Achates Power HD Demo Technical Review)

This paper provides a further technical update, with additional information on low-load cycle (LLC) and idle NO_x.

CARB put in place LLC and idle NO_x limits as part of their Heavy-Duty Low NO_x Omnibus Regulation, approved in August 2020. The regulations apply first in 2024, and then get tougher in 2027. These regulations are intended to more fully capture the set of conditions where diesel engines operate in real world use, including in congested areas where the impact of air pollution is often highest. Research cited[1] by CARB shows that some current engines emit around 1 g / bhp-hr of NO_x during the LLC.

Summary

- Based on engine measurements and analysis, the 10.6L opposed-piston diesel engine generates 0.021 g / bhp-hr NO_x over the CARB Low-load Cycle, 60% below the 2027 ultralow NO_x limit (98% below some current engines).
- The engine also emits 4 g / hr NO_x at idle, 20% below the 2027 limit (99.9% below the current optional CARB Clean Idle standard)
- The engine can meet all 2027 CO_2 and criteria emissions from EPA and CARB with considerable margins.
- The measured results are achieved with a conventional single SCR, underfloor aftertreatment systems providing a significant advantage in cost and complexity vs. other ultralow NO_x solutions.

Low-load Cycle

The Low-Load Cycle has a long duration (over 1.5 hours) to ensure continuous active thermal management of the aftertreatment is utilized. The LLC NO_x limit from 2024-2026 is 0.2 g / bhp-hr. For 2027 and beyond, the limit drops to 0.05 g NO_x / bhp-hr.

Based on experimental tests of the Achates Power 10.6L OP diesel engine, combined with analysis from a catalyst partner using their fully aged aftertreatment system models, the heavy-duty OP engine is capable of meeting the toughest LLC regulation (0.05 g NO_x / bhp-hr) with considerable engineering margin using only currently available, underfloor aftertreatment systems. (Most efforts to meet the CARB ultralow NO_x regulations with conventional engines utilize some combination of close-coupled SCR, dual DEF dosing, electric exhaust heating, cylinder deactivation, and heated DEF dosers. NREL[2] and others estimate the cost of these additional components at \$5,000 - \$10,000 per engine. These additional costs are avoided with the OP engine.).

[1] https://www.arb.ca.gov/lists/com-attach/1-hdomnibus2020-VDdXMFIhU2IAWQIw.pdf
[2] https://www.arb.ca.gov/lists/com-attach/8-hdomnibus2020-1jACGvmafqDgElXk.pdf

The aftertreatment system considered in the analysis is a one-box solution from Eberspaecher with a current production catalyst layout including a diesel oxidation catalyst (DOC), a diesel particulate filter (DPF), a selective catalyst reduction (SCR) catalyst, and an ammonia slip catalyst (ASC), all common aftertreatment system components.

The OP engine has unique and significant advantages in the ability[3] to generate high exhaust enthalpy and very low engine out NO_x, via engine calibration with no additional heat sources, when required to bring the SCR catalysts within the thermal band required for effective NO_x mitigation. This capability is effective in cold starts and warm starts to meet ultralow NO_x regulations for FTP and RMC cycles. It is also effective for low-load cycles.

The analysis was run by taking engine-out measurements from the Achates Power 10.6L engine following the low-load cycle speed and load and analyzed by the catalyst partner using their aftertreatment system models. The models were for aged systems after 435,000 miles of operation.

Figure 1 shows temperatures at three locations – turbine out, DPF out, and SCR in. Throughout the cycle, the engine operation is adjusted to generate additional exhaust heat as required to keep the SCR in an effective temperature range.

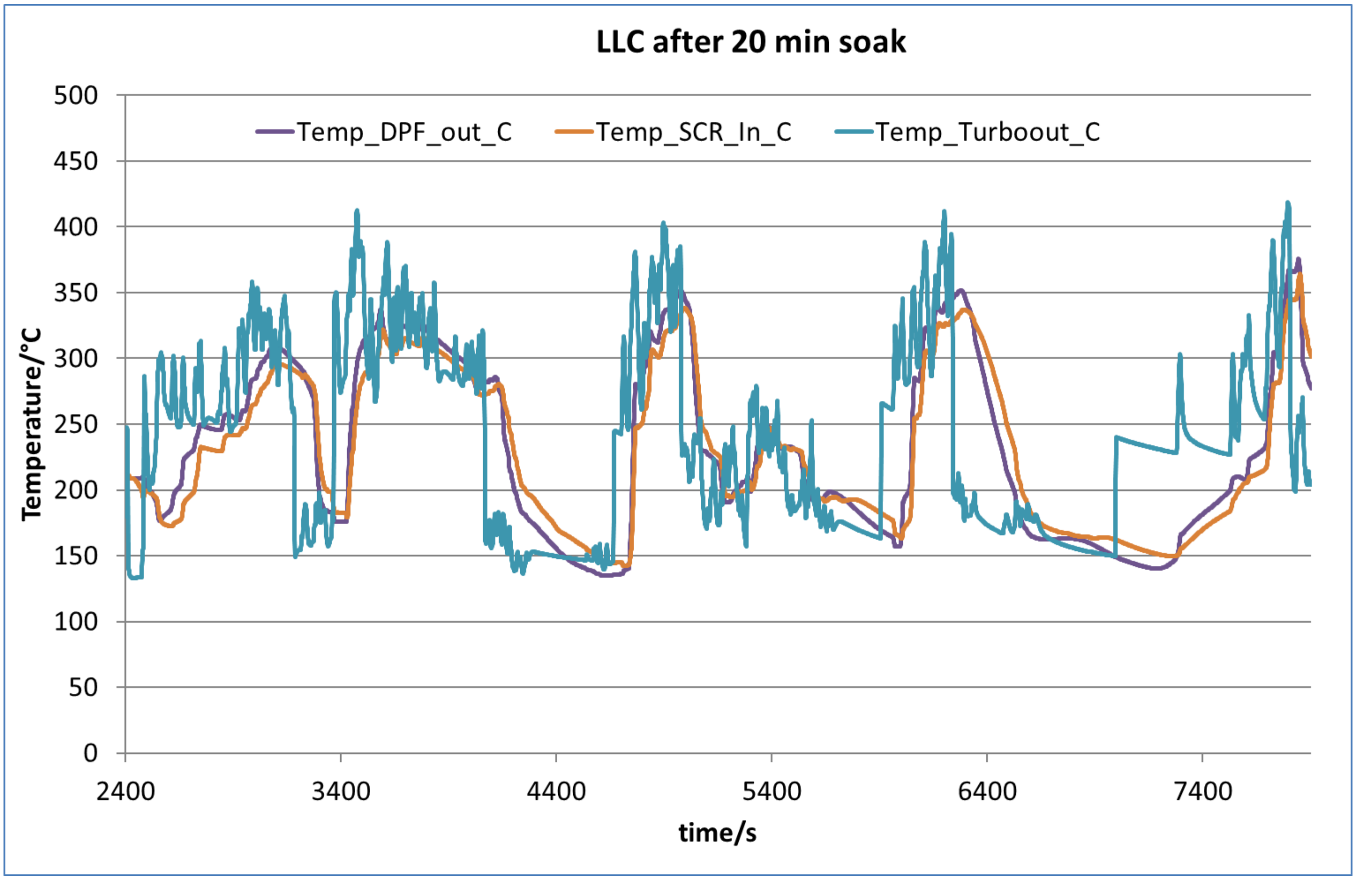

Figure 1: Temperature out of the turbo, out of the DPF, and into the SCR over the LLC

[3] https://achatespower.com/wp-content/uploads/2019/12/2018-01-1378.pdf

Figure 2 shows NO_x as it enters the SCR (in red; left hand scale) and at the tailpipe (in blue; right hand scale). Nearly all the NO_x emitted from the tailpipe during the low-load cycle occurred during just two events. Even with these two emission events, the cumulative LLC NO_x is 0.021 g / bhp-hr, nearly 60% below the 2027 requirement of 0.05 g / bhp-hr (and nearly equivalent to the RMC and FTP limits of 0.02 g / bhp-hr) and 98% below the typical current emissions, noted above.

Given these are initial results with little optimization, improvements in results are expected with additional calibration effort.

With closed loop control of the active thermal management system, ultralow NO_x operation on off-cycle low-load operation can be achieved.

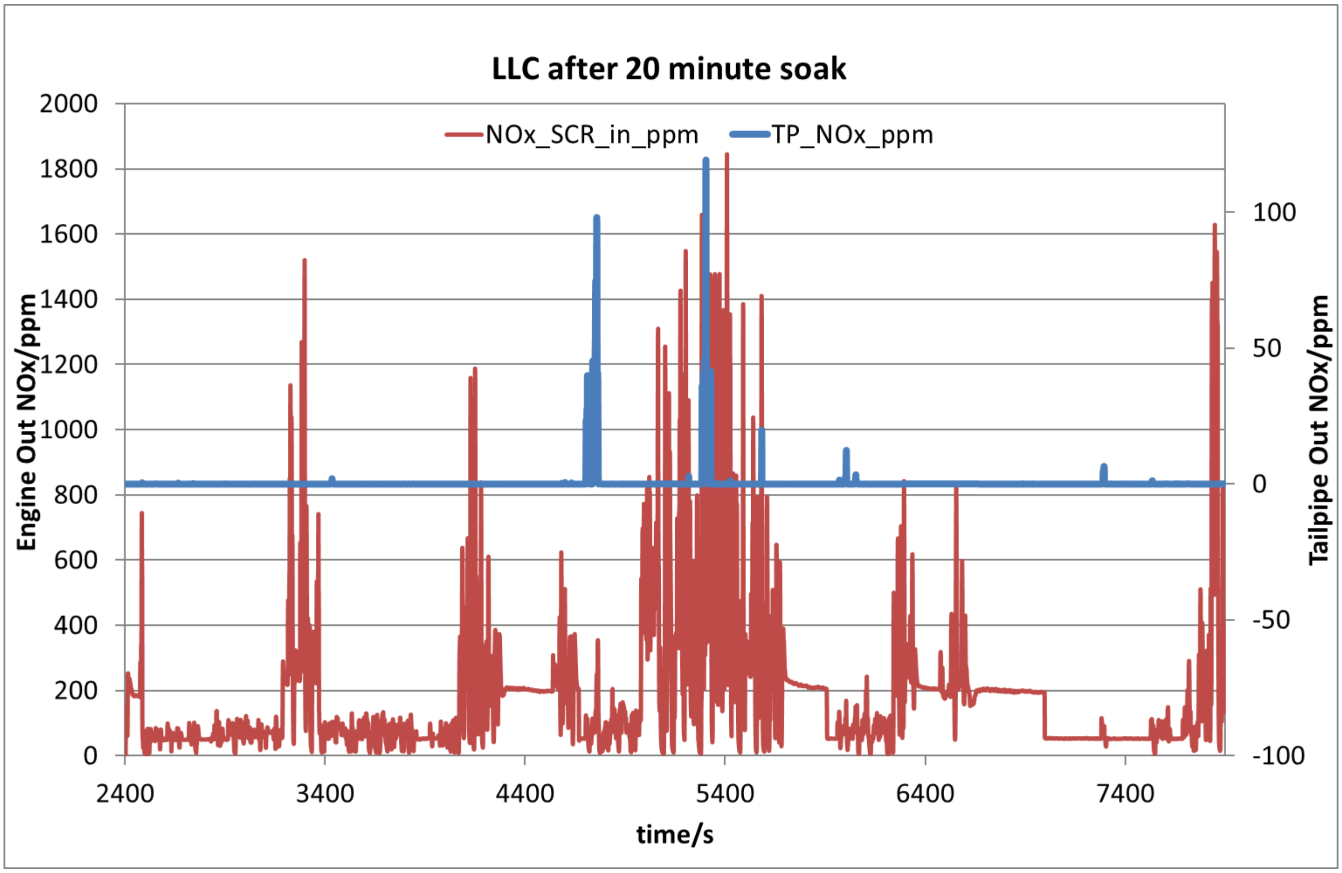

Figure 2:NOx into the SCR and out of the tailpipe over the LLC

Idle

CARB currently has an optional clean idle standard of 30 g / hr of NO_x. The new regulation calls for a mandatory idle limit of 10 g / hr in 2024-2026, and 5 g / hr in 2027 and beyond. In lieu of meeting the standard, engines maybe equipped with an engine shutdown system.

Another low NOx advantage of the OP engine is its ability to dynamically control the scavenging ratio and, therefore, trapped conditions by managing how much boost is providing to the intake air to control the pressure differential between intake and exhaust manifolds. At idle and low-loads, the engine is not consuming a lot of fuel so it does not need a lot of air. In these conditions, the engine is only partially scavenged, leaving exhaust gas in the cylinder. Similar to exhaust gas recirculation (EGR) (but even better because no energy is expended in pumping the exhaust gas out and back in again), the retained exhaust gas inhibits NO_x formation. Indeed, without an aftertreatment system at all, the 10.6L OP engine generates just 4 g / hr of NO_x at idle, 20% below the 2027 clean idle standard.

Moreover, exhaust mass flow is low during idle; the increased residence time in the aftertreatment system helps conversion efficiency.

Taken together, experimental measurements coupled with analysis by the catalyst partner using their aftertreatment system models yields idle NO_x of 0.02 g / hr, 99.6% below the 2027 clean idle standard and 99.9% below the current optional clean idle standard.

Summary

A series of measurements and analysis of the 10.6L opposed-piston diesel engine shows that it is extraordinarily well-suited to meet industry goals to significantly reduce CO_2 and criteria emissions, most notable NO_x. These advantages extend to low-load and idle conditions.

Current results are well below 2027 regulatory limits for NO_x (from CARB) and CO_2 (from EPA), as shown in the table below:

	Milestone 3.5 Engine and BASF Analysis	2027 Regulatory Limits (CARB/EPA)	Improvement vs. 2027 Standards
SET Cycle	*0.014 g/hp-hr NO_x* **415 g/hp-hr CO_2**	0.020 g/hp-hr NO_x 432 g/hp-hr CO_2	30% 4%
FTP Cycle	*0.007 g/hp-hr NO_x* **465 g/hp-hr CO_2**	0.020 g/hp-hr NO_x 503 g/hp-hr CO_2	65% 8%
Low Load Cycle	*0.021 g/hp-hr NO_x*	0.050 g/hp-hr NO_x	58%
Clean Idle	*0.02 g/hr NOx*	5 g/hr NO_x	99.6%

Key: **Measured from steady state and transient**
Modeled based on measured engine out

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