TECHNOLOGY FEASIBILITY FOR HEAVY-DUTY DIESEL TRUCKS IN ACHIEVING 90% LOWER NOx STANDARDS IN 2027

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Executive Summary

The transportation sector was responsible for over 7 million tons of NOx emissions in the U.S. in 2014, with 50% of this sector's NOx attributed to heavy-duty on- and off-road vehicles and equipment. NOx is a precursor for both ground level ozone and secondary $PM_{2.5}$ which are regulated under the National Ambient Air Quality Standards (NAAQS) because of their adverse effects on human health and the environment. Due to the continued exposure of millions of Americans to poor air quality, both the United States Environmental Protection Agency (EPA) and California Air Resources Board (CARB) have announced rulemakings focused on revising the heavy-duty truck emission standards, with a particular focus on tighter limits for oxides of nitrogen (NOx). EPA is targeting implementation in the 2027 timeframe while CARB is focusing efforts on phasing in more stringent standards in 2024 and again in 2027 with the hope of aligning with EPA as a national standard.

This report is a companion to a report released by MECA on June 10, 2019, in which we provided our assessment of technologies being commercialized by component suppliers, including MECA members, to help their customers comply with a future NOx standard of 0.05 gram/brake horsepower-hour (g/bhp-hr) for model years (MY) 2024-2026 (MECA, 2019). In this report, we present dynamometer test results and emission models from fully aged aftertreatment systems installed on heavy-duty on-road engines to offer several compliance paths that are technologically and economically achievable by MY 2027. The models used have been optimized over decades of testing of accelerated aged commercial catalysts and validated against real world emission control systems. The technologies outlined in this assessment are either commercial or market ready options that can be deployed on vehicles by model year 2027 to achieve 0.02 g/bhp-hr on the heavy-duty FTP certification cycle and approximately 0.075 g/bhp-hr in low load operation using the low load certification cycle being proposed by CARB. It is important to note that there are multiple technology paths to achieve these low levels of NOx emissions, while simultaneously lowering greenhouse gas emissions, in effect overcoming the conventional NOx versus CO_2 trade-off.

The following assessment is based on the implementation timeline and regulatory provisions presented by CARB staff at the September 26, 2019 public workshop. CARB staff signaled a plan to align the regulatory provisions for the second phase of NOx tightening with the third implementation stage of the Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles - Phase 2 (hereafter "Phase 2 GHG regulation") in 2027. Assumptions include that the OEMs will have to meet a Federal Test Procedure (FTP) certification standard with current cold start and hot start weightings, a Ramped Modal Cycle Supplemental Emission Test (RMC-SET) and the proposed Low Load Cycle (LLC) based on profile LLC-7 (CARB, 2019). Included, as part of future requirements, is a revised heavy-duty in-use testing (HDIUT) protocol that replaces the current not-to-exceed (NTE) based protocol with a moving average windows method with no low power exclusion. The technologies considered in this assessment are assumed to be designed to meet the current full-useful life (FUL), which is 435,000 miles for Class 8 heavy-duty vehicles. It should be noted that CARB is currently considering longer FUL and warranty requirements for MY 2027 and later vehicles, but there is not enough real-world data on parts past 435,000 miles to sufficiently calibrate the models used in this analysis.

The conclusions in this paper can be summarized as follows:

1. Engine and powertrain emission control technologies can enable simultaneous reductions in CO_2 and NOx by 2027.

Penetration of fuel saving technologies into the heavy-duty fleet has been spurred by EPA's Heavy-Duty Greenhouse Gas Phase 1 Standards, and EPA envisions further penetration of these technologies in order for trucks to meet future Phase 2 requirements. At the same time, research undertaken by multiple teams as part of the Department of Energy's SuperTruck I program has demonstrated how these technologies can be combined to achieve a 16% boost in fuel economy and improved freight efficiency. Participants in the SuperTruck II program are in the process of demonstrating even greater gains in fuel and freight efficiency. Component suppliers have continued to innovate, and a number of technologies that were not even considered as compliance options in the Phase 2 rule are now likely to be deployed on limited engine families in 2024 and more broadly in 2027. Furthermore, engine efficiency technologies like the ones described in this paper – such as cylinder deactivation, advanced turbochargers, , and hybridization – have also been demonstrated in combination with advanced aftertreatment technologies on heavy-duty diesel engines. Testing has shown the ability of several advanced engine technologies to be optimized to improve fuel efficiency while increasing exhaust temperature in diesel engine exhaust, which improves NOx reduction performance. It has now been widely demonstrated that the traditional trade-off relationship between CO_2 and NOx emissions at the tailpipe has been overcome and reductions of both pollutants can be achieved simultaneously through the use of commercially available technologies.

2. Engine and aftertreatment technologies can achieve an FTP and RMC emission limit of 0.02 g/bhp-hr and a Low Load Cycle (LLC) limit below 0.075 g/bhp-hr.

Engine technologies, advancements in engine calibration, thermal management, and advanced catalysts can be combined to enable engines plus aftertreatment systems to achieve FTP and RMC emissions below 0.02 g/bhp-hr NOx. Ongoing work is aimed at demonstrating levels that will provide sufficient compliance margins that OEMs need for full useful life durability. During cold-start and low-load operation, engine technologies can be combined with calibration and thermal management to reduce engine out NOx emissions and provide additional heat to aftertreatment systems. New aftertreatment architectures, that employ a close-coupled SCR catalyst before the DOC+DPF in a twin SCR system arrangement with dual urea dosing, can meet future NOx limits proposed to phase in from 2024 to 2027. The approaches discussed for meeting 2027 NOx limits utilize commercially available engine technologies, improved thermal management, and advanced aftertreatment system designs based on high efficiency catalysts and coating strategies. Aftertreatment conversion models and engine testing demonstrate the ability to achieve ultra-low NOx levels under real-world heavy-duty vehicle operation.

3. The estimated cost of future emission controls for a Class 8 tractor meeting 2027 NOx targets of 0.02 g/bhp-hr over the FTP and RMC is estimated to add about $1,500 to $2,050 to the cost of a MY 2027 Class 8 truck.

In our cost analysis, we estimated a cost range of current heavy-duty emission controls systems on the road today. The costs of hardware to meet today's NOx requirements were estimated for two engine sizes, 6-7L and 12-13L, representing a large fraction of current heavy-duty engine sales. The former is often found in Class 4-6 heavy-duty vehicles while the latter is found in Class 7-8 vehicles. Our cost estimate for current aftertreatment systems on a vehicle with a 6-7L engine is about $2,600 to $3,500. For a Class 8 line-haul tractor with a 12-13L engine, we estimate the cost of the hardware to be in the range of $3,500 to $4,600 per truck. Since 2010, engine calibration and exhaust system optimization have reduced the cost of 2019 emission controls while truck prices have continued to rise at a historic level of approximately 1% per year, resulting in the emission control system cost constituting a smaller portion of today's total truck price.

We also estimated the cost of a 2027 emission control system including engine improvements being considered by CARB to meet an FTP tailpipe certification NOx value of 0.02 g/bhp-hr and a future LLC certification requirement with current durability and warranty requirements. For a vehicle with a 6-7 liter engine, the incremental hardware improvements needed to meet a 0.02 g/bhp-hr certification limit on the FTP cycle and future LLC standard at today's durability and warranty requirements were estimated to add about $1,300 to $1,800 to the cost of the engine efficiency and emission control technologies. For a Class 8 tractor with a 12-13 liter engine similar incremental improvements were estimated to add about $1,500 to $2,050 (less than 1.2%) to the cost of a MY 2027 truck, estimated to be approximately $177,000, based on a historical 1% annual rate of MSRP increase reported by ICCT.

Finally, we estimated the cost of a 2027 emission control system that meets an FTP tailpipe certification NOx value of 0.02 g/bhp-hr and a future LLC certification requirement as well as longer durability and warranty requirements of a 1 million mile useful life (FUL) and 800,000 mile warranty for class 8 and 550,000 mile FUL and 440,000 mile warranty for Class 4-7 starting in 2027. For a 6-7 liter engine, the estimated incremental costs to meet the durability and warranty requirements assumed to be implemented in MY 2027 were $1,800 to $2,450. For a Class 8 tractor with 12-13 liter engine, these increased durability and warranty requirements were estimated to add $2,000 to $2,750 to the cost of the emission control and engine efficiency technologies. Therefore, the estimated total additional emission control cost to meet a 0.02 g/bhp-hr FTP tailpipe limit, LLC limit, 1-million-mile durability requirement and 800,000 mile warranty would be $3,100 to $4,250 for 6-7 liter engines and $3,550 to $4,800 for 12-13 liter engines.

1.0 Background

Nitrogen oxides (NOx) include seven compounds that contain nitrogen and oxygen in varying forms. The United States Environmental Protection Agency (EPA) regulates nitrogen dioxide (NO_2) as a surrogate for NOx as well as nitrous oxide (N_2O) due to this compound's negative effect on climate. In addition to causing adverse health effects, NOx participates in atmospheric chemical reactions to produce ozone, acid rain and fine particulate matter ($PM_{2.5}$). Because NO_2, ozone and $PM_{2.5}$ lead to adverse health outcomes, EPA established and routinely updates National Ambient Air Quality Standards (NAAQS) for these air pollutants in order to protect public health and welfare. There are currently approximately 100 million people living in areas that exceed the 2015, 8-hr ozone NAAQS level of 70 ppb and over 38 million people living in areas that exceed the 2012 $PM_{2.5}$ NAAQS of 12 $\mu g/m^3$ (U.S. EPA, 2019). One of the mechanisms to reduce ozone and secondary $PM_{2.5}$ concentrations is to reduce their precursor compounds, including NOx and volatile organic compounds (VOC).

The transportation sector was responsible for over 7 million tons of NOx emissions in 2014 (U.S. EPA, 2017). This is over 50% less than the NOx emissions inventory in 1970, primarily due to increasingly stringent highway vehicle tailpipe standards. While diesel engines were once responsible for high NOx emissions, engines and vehicles that are produced today must meet stringent NOx standards of 0.2 gram per brake horsepower-hour (g/bhp-hr). New engines and vehicles have largely achieved these low levels by employing selective catalytic reduction (SCR) in combination with cooled exhaust gas recirculation (EGR). However, current engines continue to have challenges maintaining low NOx emissions during low engine load conditions, which is mainly due to federal in-use compliance requirements that allow exclusion of emissions data reporting at times of challenging operational conditions (e.g., lower vehicle speeds, engine loads and aftertreatment temperatures). In the MECA white paper released in June 2019, we presented information about the new low load certification cycle (LLC-7) that CARB proposes to introduce in 2024 (MECA, 2019). The LLC has an average engine power level of about 7-8%, which is below the European VI-D heavy-duty in-use compliance program that allows exclusion of data below 10% engine power. This new test cycle is aimed at addressing low speed and load operation at a power level below the current FTP (21% average power) to ensure aftertreatment is functioning in these challenging operating conditions.

MECA funded a study at the National Renewable Energy Laboratory (NREL) that summarized statistics of real world operation from two major data sources: NREL's Fleet DNA database that includes 435 conventional, diesel-powered trucks from 25 different vocations and from 24 fleets across the U.S. and University of California Riverside's CE-CERT database that consists of 79 diesel-powered vehicles from 10 different vocations and from 23 fleets operating in California (Zhang, Miller, Kotz, Kelly, & Thornton, 2019). Results from this report provide some insights into the causes for NOx emission reduction challenges due to real world operation. Some observations from this work include:

- Cold start represent approximately 12% of total real-world starts, and this is appropriately reflected by the FTP composite weighting of 14.3%.
- Cold operation time is also well captured by the FTP certification cycle (1.5%) versus 1.3% in the real-world.

- Current cold and hot start definitions are based on coolant temperature, which does not often correlate with SCR inlet temperature and thus SCR performance.
- Much of real-world operation (30-70%) involves restarting a hot engine (based on coolant temperature), but the aftertreatment has cooled off below the optimal operating temperature and must be warmed back-up quickly to minimize NOx emissions.
- Engines idle much more in the real world than captured by inventory emission models or certification cycles.

As noted above, hundreds of millions of people in the U.S. and around the world still breathe unhealthy air. Large populations of citizens in the U.S. live in regions that are in ozone nonattainment that would benefit from clean heavy-duty engines. A MECA funded emission inventory based on EPA's MOVES model concluded that the adoption of a 0.02 g/bhp-hr national NOx standard, assuming implementation beginning in 2021 could result in significant NOx reductions by 2030 of approximately 350 tons per day (tpd) in the contiguous U.S. outside of California (MECA, 2018). When fully incorporated into the heavy-duty on-road fleet, national standards that are 90% below 2010 limits would achieve 730 tpd of NOx reductions in 2050. While the timeline for implementation has been delayed to 2024 and 2027, this analysis is still a reasonable estimate of the magnitude of emissions benefits if one factors in the likely delay for implementation of three to six years.

MECA estimated that these NOx reductions can be achieved with an approximate cost effectiveness from $1,000 to $5,000 per ton of NOx reduced for a Class 8 line-haul tractor. We used a cost effectiveness methodology that is based on both certification emission levels (upper bound) as well as in-use emissions (lower bound) reported by CARB (Hu, et al., 2019) following the 2017 Carl Moyer Guidelines (CARB, 2017), and assuming typical heavy-duty engine power, load and annual use. Benefits were calculated for a Class 8 vehicle's current full useful life of 435,000 miles. The resulting range of cost effectiveness values is due to variability in assumptions of NOx emission reductions on the test cycle versus real-world NOx emissions reported by CARB and used by the Carl Moyer program. EPA's estimate of $2,000 per ton NOx reduced for the 2010 on-highway heavy-duty NOx standards is within this range (40 CFR Parts 69, 80, and 86, 2001), and both are significantly below the average cost of controls on stationary power plants and industrial NOx sources, which have been reported to range from $2,000-$21,000 per ton (U.S. EPA, 2017). Similarly, CARB estimated the cost effectiveness for future low-NOx requirements proposed for 2027 to be approximately $6,000 per ton (CARB, 2019). A more detailed discussion of the technology costs can be found in Section 3.6.

This paper discusses advancements in NOx emission control technology that are found on some light-duty vehicles and being offered by suppliers for commercial vehicles to reduce NOx to ultra-low levels. This paper particularly focuses on the feasibility of heavy-duty engines to achieve 0.02 g/bhp-hr on the FTP and RMC certification cycles and 0.075 g/bhp-hr in low load operation by MY 2027 while not impacting fuel economy.

2.0 Overview of Engine and Powertrain CO_2 and NOx Emission Control Technologies

EPA's Heavy-Duty Phase 2 Greenhouse Gas Standards, finalized in 2016, considered a number of technologies that vehicle manufacturers are likely to deploy to comply with the 2027 CO_2 standards. The Department of Energy's SuperTruck I program has demonstrated how these technologies can be combined to achieve a 50% brake thermal efficiency from the engine, equivalent to a 16% boost in fuel economy, and further reduce CO_2 per ton-mile by deploying vehicle technologies. Participants in the SuperTruck II program are in the process of demonstrating even greater gains in fuel and freight efficiency. In the three years since the standards were finalized and the first SuperTruck program, component suppliers have continued to innovate, and a number of technologies that were not even considered as compliance options in the Phase 2 rule are now likely to be deployed on limited engine families in 2024 and more broadly in 2027. Some of these technologies are being tested as part of the CARB Low NOx test program at SwRI and are presented in this section.

2.1 Cylinder Deactivation

Cylinder deactivation (CDA) is an established technology on light-duty vehicles, with the primary objective of reducing fuel consumption and CO_2 emissions. This technology combines hardware and software computing power to in effect "shut down" some of an engine's cylinders, based on the power demand, and keep the effective cylinder load in an efficient portion of the engine map without burning more fuel by reducing the number of cylinders firing during lower load operation.

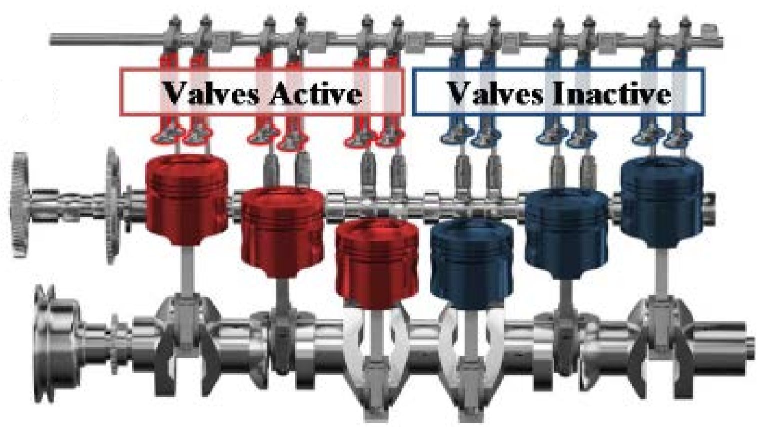

Figure 1. Cylinder deactivation (6 cylinder engine shown).

The technology, illustrated in Figure 1, uses solenoids on the valve lifters to keep intake and exhaust valves closed when a cylinder is deactivated while simultaneously shutting off fuel to the deactivated cylinder. Rather than pumping cold intake air into the exhaust system during coasting or idling, the valves are closed, allowing the deactivated cylinder to act as a spring as the piston moves up and down the bore. Closing the valves eliminates most of the normal pumping losses that reduce the engine fuel efficiency and thermal energy due to cold air being pumped through the exhaust. Deactivating a portion of the cylinders causes the remaining active pistons to work harder within a more efficient part of the engine operating regime, thus increasing fuel economy and generating more heat to get the aftertreatment hot faster. In addition, shutting off an engine's cylinders during deceleration and idling reduces air flow through the engine and exhaust to enable heat retention in the exhaust system. Both of these conditions, enabled by CDA, improve the SCR's ability to effectively reduce NOx emissions. During low load operation, CDA has resulted in exhaust temperatures increasing by 50°C to 100°C when it is most needed to maintain effective conversion of NOx in the SCR. In some demonstrations, CDA has been combined with a 48V mild hybrid motor with launch and sailing capability to extend the range of CDA operation over the engine, and this may deliver multiplicative CO_2 reductions from these synergistic technologies.

The frequency of deactivation of a cylinder can be a set program built into the engine calibration or a microprocessor can be added to "dynamically" deactivate each cylinder. Dynamic CDA is a variation of CDA that allows all cylinders in an engine to be deactivated in order to balance power demands with engine operation. For dual mode CDA, specific cylinders are designed as either on or off, and the CDA may be only activated in certain regions of the engine map. In dynamic CDA the controller selects which cylinders to deactivate prior to each combustion event as to avoid known resonance patterns within the engine, which can lead to noise, vibration and harshness. Dynamic CDA can vary the combination of cylinders firing as often as thousands of times per minute, providing more opportunities for CDA operation. Dynamic CDA has been installed on several production engines and has delivered simultaneous NOx and CO_2 reductions.

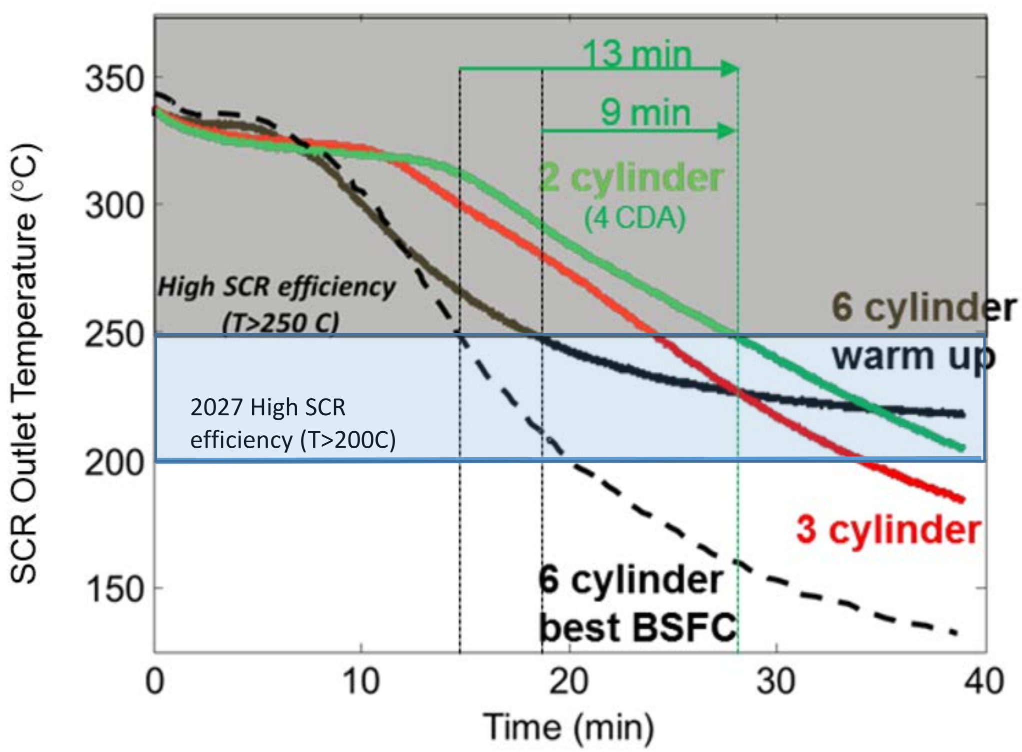

Figure 2. Benefit of CDA on longer time maintaining SCR outlet temperature after engine drops to idle.

CDA has been a proven technology on light-duty vehicles for decades, and it is now being adapted to heavy-duty diesel engines. On a diesel engine, CDA is programmed to operate differently than on gasoline engines, with the goal of the diesel engine running hotter in low load situations by having the pistons that are firing do more work. This is particularly important for vehicles that spend a lot of time in creep and idle operation modes. Figure 2 shows the benefit of employing CDA when an engine drops to idle after high load operation (Allen, et al., 2019). The dashed black line shows the rate of SCR outlet temperature decline of the engine when operating in its most fuel-efficient calibration. The solid black line shows the ability to add heat to the exhaust by burning fuel. By deactivating three cylinders (red line) or four cylinders (green line), the exhaust temperature can be maintained hotter for a longer duration without burning extra fuel.

In the MECA 2024 technology white paper released in June 2019, we presented dynamometer testing on the FTP cycle with CDA installed on a medium-duty engine, which showed a 3.4% fuel economy improvement when the engine was calibrated for stay hot operation with CDA initiated below 3 bar brake mean effective pressure (BMEP) after 900 seconds into the cold cycle (MECA, 2019). When the engine was operated on the Orange County Bus Cycle, the approximate fuel saving was 5.6% using the same stay-hot calibration. A slightly different calibration utilizing CDA below 3 bar BMEP for the entire cycle yielded 8.7% fuel savings, which is indicative of benefits from real world operation. Similarly, when operated over a drayage cycle, a fuel efficiency anywhere from 4 to 35% may be realized (using CDA below 3 bar BMEP), depending on operating mode (Figure 3) (Joshi, et al., 2018). The fuel economy benefit depends on the amount of time an engine spends in low load operation, with the highest gains seen when an engine is frequently operated at low load.

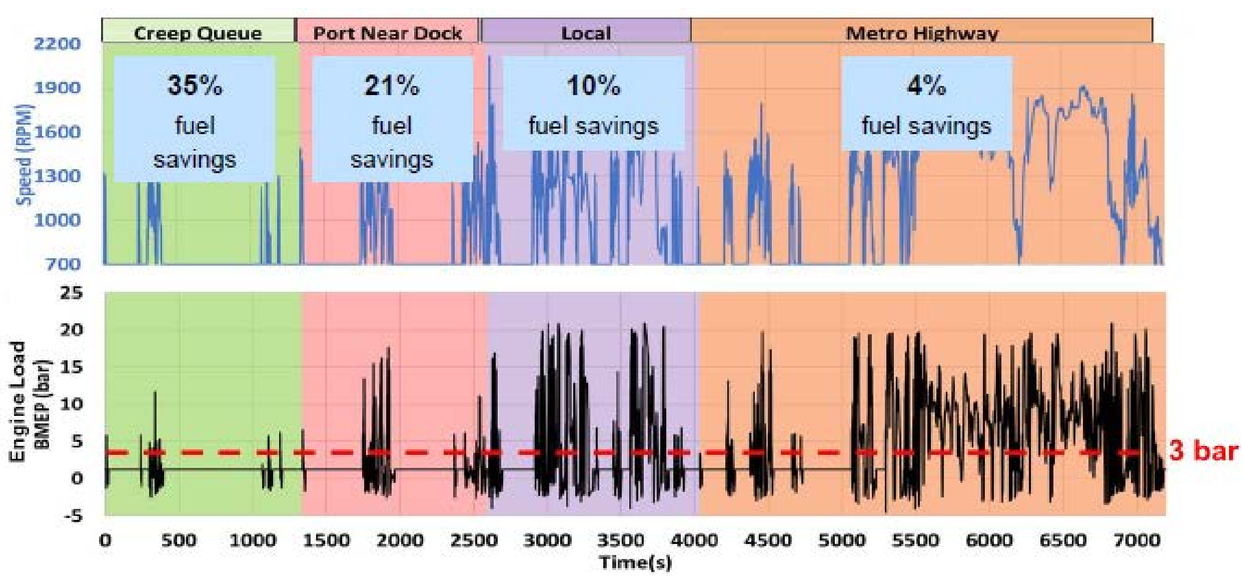

Figure 3. Fuel economy benefits of running half engine CDA below 3 bar during operation of a medium duty diesel engine over a port drayage cycle.

Recent testing was conducted on a Cummins X15 engine with its production aftertreatment and with and without CDA implemented. The engine plus aftertreatment were tested over several drive cycles, including the FTP, LLC, US Beverage Cycle, New York Bus Cycle, and Orange County Bus Cycle. Higher SCR temperature resulting in improved NOx reduction as well as simultaneous fuel savings were demonstrated when CDA was implemented. The results are summarized in Table 1.

Table 1. Results of Cummins X15 stock engine with CDA compared to baseline engine configuration without CDA.

Drive Cycle	SCR Temperature Increase Over Baseline	NOx Reduction Over Baseline	Fuel Savings Over Baseline
US Beverage Cycle	+ 24 °C	67%	5.0%
New York Bus Cycle	+ 14 °C	33%	7.8%
Orange County Bus Cycle	+ 17 °C	86%	3.2%

CDA has also been demonstrated in combination with advanced aftertreatment technologies on heavy-duty diesel engines. Testing in conjunction with the CARB Low-NOx Demonstration Program at SwRI has shown the ability of CDA to increase exhaust temperature in diesel engine exhaust while increasing fuel efficiency. The combination of CDA and an advanced aftertreatment configuration that includes twin SCR catalysts, with one SCR unit in the close-coupled position, was able to achieve 0.018 g/bhp-hr over the composite (cold plus hot) FTP and 0.12 g/bhp-hr over the LLC (Table 2) (Neely, Sharp, Pieczko, & McCarthy, 2020).

Table 2. Results from testing Cummins X15 engine with CDA plus advanced aftertreatement.

	Engine Out NOx	Tailpipe NOx	Reduction
Cold FTP	2.8 g/bhp-hr	0.040 g/bhp-hr	98.6%
Hot FTP	3.3 g/bhp-hr	0.014 g/bhp-hr	99.6%
Composite FTP		0.018 g/bhp-hr	
LLC	3.3 g/bhp-hr	0.120 g/bhp-hr	96.0%

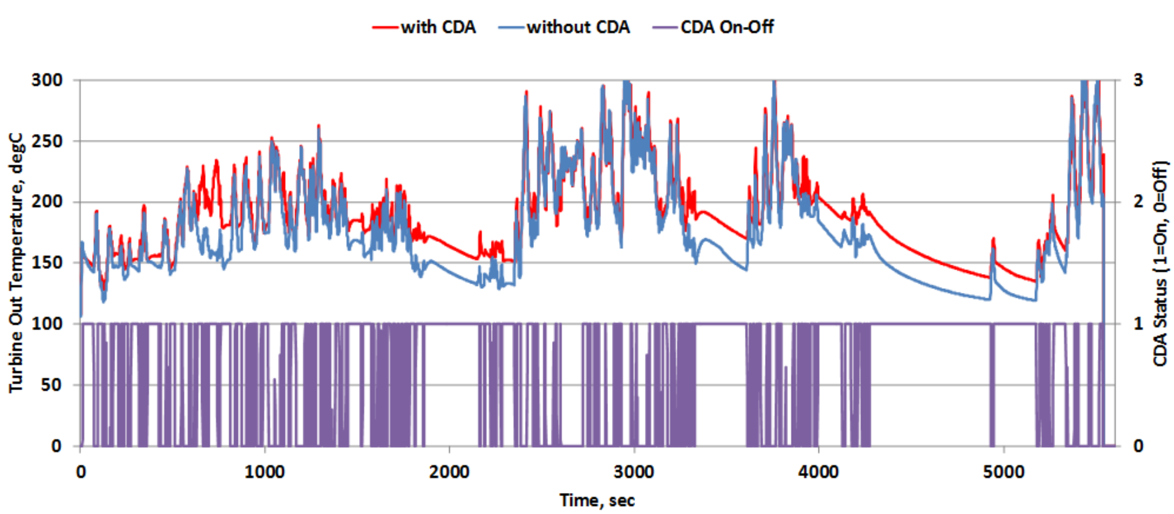

Figure 4. Exhaust temperature increase as a function of cylinder deactivation in a low load cycle.

Figure 4 is a plot of real on-engine test data from dynamometer testing conducted at Southwest Research Institute as a part of the CARB Low-NOx Demonstration Program (Sharp, 2019). CDA was used 60% of the time in this low load cycle and resulted in significant increased exhaust temperature primarily during motoring or idling. CDA is a technology that supports retaining heat in the emission controls during the idle or motoring portions of the cycle shown by the CDA-off operation depicted in the lower portion of Figure 4.

2.2 Advanced Turbocharger (Turbo) Technologies

Turbochargers are used by heavy-duty engine OEMs to improve fuel efficiency and reduce emissions. Turbochargers also make it possible to downsize the engine to further reduce fuel consumption without sacrificing peak torque and power. A turbo can increase engine power by pumping air into the combustion chambers at higher-than-atmospheric pressure, which allows more fuel to be burned, resulting in higher output. A typical turbo is driven by exhaust gases by routing these gases through a turbine. The turbine is attached to a shaft which has a compressor mounted on the opposite end. Engine exhaust rotates the shaft at speeds above a hundred-thousand rpm, which in turn compresses the air entering the engine's intake manifold. Because the act of compressing air results in the air heating, which is undesirable, intercoolers are commonly installed with turbos. The latest high efficiency turbochargers are one of the more effective tools demonstrated on the DOE SuperTruck program (Navistar, 2016).

In addition to affecting the power density of the engine, turbochargers play a significant role in NOx and CO_2 regulations compliance. Continuous improvement in turbocharger technology is making it possible to run very lean combustion (high air/fuel ratios) which is fast and efficient. This allows for very low particulate generation and even low engine-out NOx. In addition, these highly efficient turbochargers affect the pumping loop in such a way that they can provide positive crankshaft work and improve brake specific fuel consumption (BSFC) and brake specific CO_2 ($BSCO_2$) as intake manifold boost pressure becomes higher than exhaust manifold backpressure. For EGR based engine strategies, this requires other technologies being developed, including EGR diverter valves upstream of the turbine that minimize EGR pumping work, and mechanically or electrically driven high-pressure loop EGR pumps. Typical EGR pump technologies include EGR "hardened" roots blowers and centrifugal compressors.

Modern turbochargers have a variety of available technology options enabling lower CO_2 emissions by improving thermal management capability, such as: i.) state of the art aerodynamics, ii) electrically-actuated wastegates that allow exhaust gases to by-pass the turbo to increase the temperature in the aftertreatment, and iii.) ball bearings to improve transient boost response. These and other technologies are available to support further reductions in CO_2 and emissions. More advanced turbochargers are designed with a variable nozzle that adjusts with exhaust flow to provide more control of intake pressure and optimization of the air-to-fuel ratio for improved performance (e.g., improved torque at lower speeds) and fuel economy. These variable geometry turbochargers (VGT), also known as variable nozzle turbines (VNT) and variable turbine geometry (VTG), also enable lower CO_2 emissions through improved thermal management capability to enhance aftertreatment light-off. Finally, modern turbochargers have enabled engine and vehicle manufacturers the ability to downsize engines, resulting in fuel savings without sacrificing power and/or performance.

Turbocompounding is a variant of turbocharger technology that allows for the mechanical energy from the exhaust gas to be extracted and added to the engine crankshaft through a transmission. Mechanical turbocompounding has been employed on some commercial diesel engines, and U.S. EPA estimates penetration to reach 10% in the U.S. by the time the Phase 2 GHG Regulation is fully implemented in 2027 (U.S. EPA, 2016). An early 2013 version of a turbocompound-equipped engine was used during the first stage of testing at SwRI under the CARB HD Low NOx Test Program, and the results from this engine with advanced aftertreatment have been summarized in several SAE technical papers (Sharp, Webb, Yoon, Carter, & Henry, 2017; Sharp, et al., 2017-01-0954, 2017; Sharp, et al., 2017-01-0958, 2017). While turbocompounding has the potential to reduce fuel consumption, it can result in lower exhaust temperatures that can challenge aftertreatment performance. It is therefore important to consider turbocompound designs that incorporate bypass systems during cold start and low load operation or electrically driven turbocompounding systems where the unit can be placed after the aftertreatment system.

As suppliers consider upcoming low-NOx requirements alongside Phase 2 GHG regulation standards, new turbo designs have been developed and are being commercialized with some OEMs. Driven turbochargers represent another technology that can be adapted specifically for emission reduction strategies. Driven turbos can be used to control the speed of the turbo machinery independently of the engine's exhaust flow and vary the relative ratio between engine speed and turbo speed. This is done by utilizing either mechanical or electrical components, coupled with a speed reduction transmission (mechanically driven) or motor generators (electrically driven), to either add or subtract power from the turbocharger shaft.

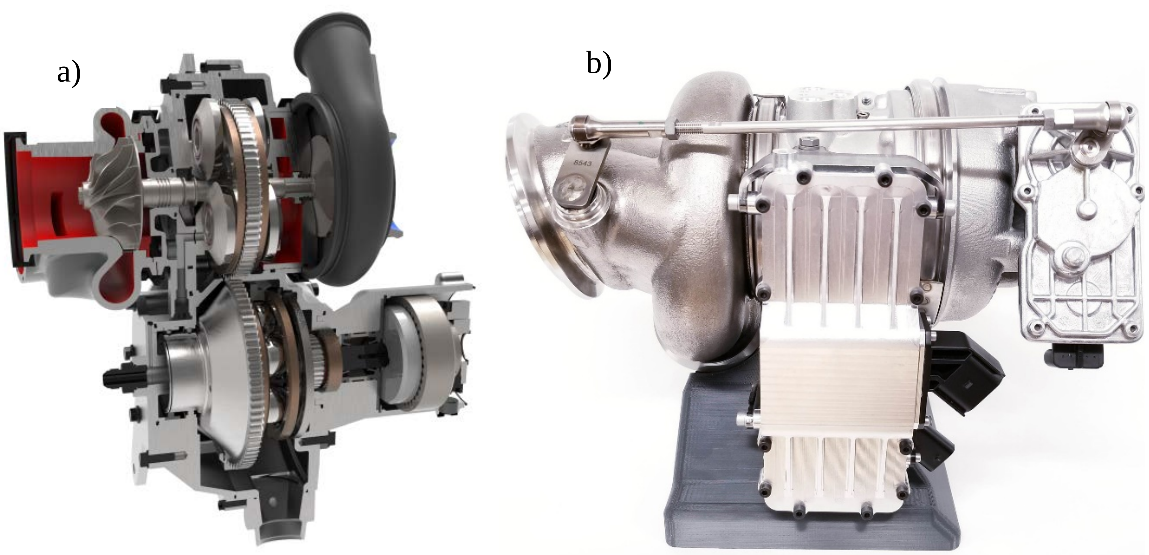

Figure 5. Pictures of: a) mechanically-driven turbocharger, and b) electrically-driven turbocharger.

Driven turbos may be utilized for several reasons, including performance, efficiency, and emissions. Considered an 'on-demand' air device, a driven turbo also receives transient power from its turbine. During transient operation, a driven turbo will behave like a supercharger and consume mechanical or electrical energy to accelerate the turbomachinery for improved engine response. Because they do not need to directly balance the turbine and compressor power, driven turbochargers can utilize different turbine and compressor designs compared to traditional (exhaust-gas-only driven) turbochargers. A driven turbo can provide more compressor power than the turbine can deliver at lower power engine operating conditions. At high speed operation, the driven turbo will return mechanical or electrical power to the engine in the form of turbo-compounding, which recovers excess exhaust power to improve efficiency. This cumulative effect lets a driven turbo perform all the functions of a supercharger, turbocharger, and turbo-compounder.

NOx emission control uniquely benefits from the application of driven turbos in several ways. Applying a driven turbo can decouple EGR from boost pressure, reduce transient engine out NOx, and improve aftertreatment temperatures during cold start and low load operation. Incorporation of a bypass valve can fully direct all exhaust flow around the turbine and directly to the aftertreatment to provide quick temperature rises when the SCR temperature drops below an optimal temperature for NOx conversion. Bypassing a driven turbine can still deliver the necessary boost pressure to the engine through supercharging, which also increases the gross load on the engine to help increase exhaust temperature. Testing has shown that routing engine exhaust to the aftertreatment by bypassing a turbocharger is one of the most effective methods to heat up the aftertreatment.

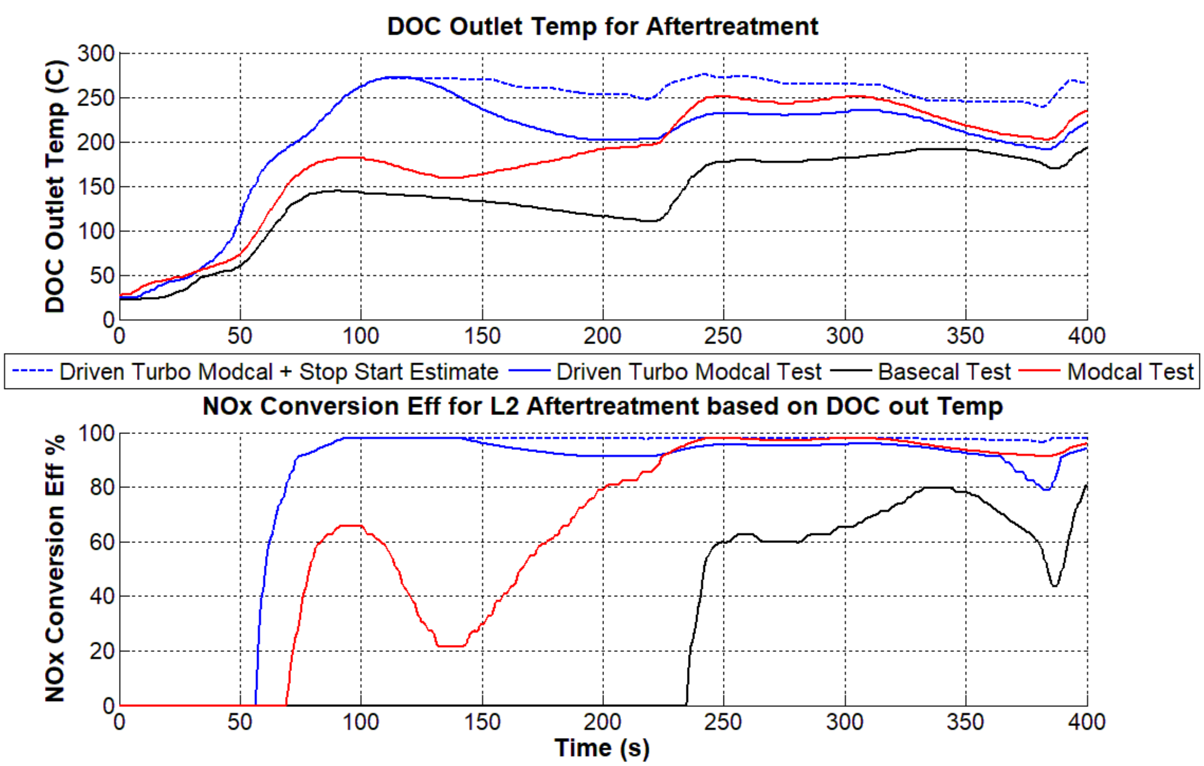

Figure 6. FTP cold start testing exhaust temperature and NOx conversion.

Testing has shown that during the first 400 seconds of the cold FTP cycle, the conversion efficiency for a mechanically driven bypassed turbo can reduce the cumulative tailpipe NOx by 50% from the baseline configuration. Furthermore, incorporating start-stop technology (described in more detail in Section 2.3 below) during idle can also keep aftertreatment hot and reduce CO_2 while preparing aftertreatment for a return to load transition and the fast boost response from supercharging. The NOx conversion efficiency gain is due to the quick rise in temperature enabled by this technology configuration combined with a modified calibration (Modcal) versus the base engine calibration (Figure 6). The fast temperature rise also allows the engine to return to its more efficient base calibration early in the cycle. Although supercharging mode will consume power, the combined effect of the rapid exhaust temperature rise, stop-start technology, late cycle turbo compounding and calibration can deliver an overall CO_2 benefit while providing the best NOx conversion early in the cycle. Driven turbos have repeatedly demonstrated CO_2 steady-state reductions of over 4% and drive cycle reductions of better than 6%.

2.3 Electrification

Electrified powertrains are quickly making their way from light-duty passenger cars to commercial trucks and buses. The technology level of electrification and penetration rate can vary across weight classes and vocations, but the conclusion that electrified powertrains are an effective tool to reduce CO_2 as well as criteria pollutants is being recognized by regulators and vehicle manufacturers. There are numerous examples of electric and electrified commercial vehicles being offered for sale and demonstrated by virtually all of the OEMs. In the 2027 timeframe suppliers anticipate that electrification will play a more significant role in helping OEMs meet future NOx and GHG standards. Both CARB and U.S. EPA have signaled consideration of electric powertrains' contribution to achieving ultra-low NOx tailpipe emissions as part of the CARB Omnibus and EPA Cleaner Trucks Initiative rulemakings.

In this section we introduce several electric technology options that will be commercially available before 2027 to allow OEMs to use electrification as a pathway to achieving simultaneous NOx and CO_2 emission reductions.

2.3.1 Mild Hybrids

As briefly discussed in our previous white paper (MECA, 2019), 48-volt mild hybrid electrical systems and components are expected to make their way onto heavy-duty vehicles in the near future. These 48-volt systems can be found on many light-duty vehicle models (primarily in the EU) from Mercedes, Audi and PSA. In the U.S., FCA is offering a 48V system on the RAM 1500 pick-up and the Jeep Wrangler under the eTorque name. Because the safe voltage threshold is 60 volts, which is especially important when technicians perform maintenance on the electrical system, 48-volt systems are advantageous from an implementation standpoint. From a cost perspective, 48-volt systems include smaller starter and wire gauge requirements, offering cost savings from a high voltage architecture of a full hybrid. The U.S. Department of Energy's SuperTruck II program teams are employing 48-volt technologies as they attempt to demonstrate trucks with greater than 55% brake thermal efficiency (U.S. Department of Energy, 2018). Figure 7 provides a diagram of a 48-volt system.

Similar to the passenger car fleet, truck OEMs are considering replacing traditionally mechanically-driven components with electric versions in order to gain efficiency. Running accessories off of 48-volt electricity rather than 12-volts is more efficient due to reduced electrical losses and because components that draw more power, such as pumps and fans, have increased efficiency when operating at higher voltages. The types of components that may be electrified include, electric turbos, electronic EGR pumps, AC compressors, electrically heated catalysts, electric cooling fans, oil pumps and coolant pumps among others. Another technology that 48-volt systems could enable is electric power take-offs rather than using an engine powered auxiliary power unit or idling the main engine during hoteling while drivers rest. Decoupling accessories from the engine reduces parasitic drag while allowing the accessories to set their own duty cycles based on vehicle and customer demands. In addition, the presence of a 48-volt power architecture on a truck retains the ability to power 12-volt accessories, with which drivers are familiar. MECA members supplying commercial 48V components for commercial vehicles believe that the technology may be feasible to apply to a limited number of engine families by 2024, and it is likely to see greater penetration by 2027, especially on Class 8 line-haul where full hybridization is less practical.

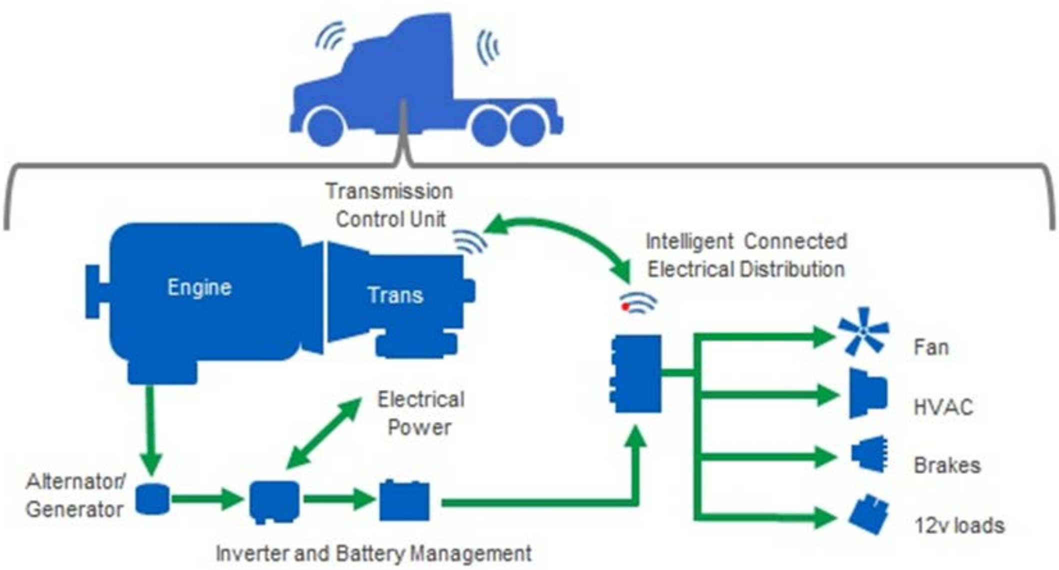

Figure 7. Schematic of a 48-volt commercial vehicle.

While there are fuel economy benefits to the application of 48-volt hybrids, the need for higher voltage systems on trucks is also being driven by other desirable fuel saving benefits such as electrifying engine or vehicle components to reduce the load on the engine and provide a mechanism to capture and store braking energy in a battery for future use when the engine is not operating to reduce the overall CO_2 emissions of the powertrain and improve fuel economy of the truck. In addition, driver safety features and other entertainment accessories are increasing vehicle electrical demand, which is stretching the capacity of current 12-volt electrical systems. Higher voltage electrical systems, such as 48-volt, could become a preferred solution to accommodate the need for more on-board power.

Mild hybridization covers a range of configurations, but a promising one includes an electric motor/generator, regenerative braking, electric boost and advanced batteries. Stop/start deployment also provides a thermal management benefit to the aftertreatment by preventing cooling airflow through the aftertreatment during hot idle conditions. In this way, 48-volt mild hybridization is complementary technology to CDA and start-stop capability, allowing the combination of multiple technologies on a vehicle to yield synergistic benefits and justify the cost.

Mild hybrid designs incorporate an electric motor and 48-volt battery along with the combustion engine and the normal 12-volt battery in today's trucks. The 48-volt configuration includes a conventional 12-volt network using a lead-acid battery like those employed in most conventional vehicles, but it adds a 48-volt lithium-ion battery with a separate 48-volt network. The 12-volt network handles traditional loads, such as lighting, ignition, entertainment, and audio systems. The 48-volt system supports active chassis systems and regenerative braking, and allows for further electrification of components such as those listed above. Because high voltage, full-hybrid electrical systems are likely to retain some 48V architecture to run the auxiliary components in addition to the higher voltage loop used to power the e-axels for propulsion. Leveraging the 48V components across multiple different hybrid powertrains will control costs through economies of scale.

Advanced start-stop systems have been developed that use an induction motor in a 48-volt belt-driven starter-generator (BSG). When the engine is running, the motor, acting as a generator, will charge a separate battery. When the engine needs to be started, the motor then applies its torque via the accessory belt and cranks the engine instead of using the starter motor. The separate battery can also be recharged via a regenerative braking system. In addition to the start-stop function, a BSG system can enhance fuel economy even during highway driving by cutting off the fuel supply when cruising or decelerating. Such systems can also be designed to deliver a short power boost to the drivetrain. This boost is typically 10 to 20 kW and is limited by the capacity of the 48V battery and accessory belt linking the motor to the crankshaft. New designs are linking the BSG directly to the crankshaft and allowing additional power boost of up to 30kW to be delivered, giving greater benefits to light and medium commercial vehicles.

Electric superchargers and turbochargers are two technologies enabled by 48-volt architectures. With the former, electric power is used to spool up the vehicle's turbo at start-up or restart and at low engine speeds to reduce or eliminate turbo lag. This results in an increase in low end torque, acceleration, and fuel economy. Electric turbochargers (described in Section 2.2 above) are driven turbos that can operate independently from the exhaust gas flowrate.

Electrically heated catalysts (EHC) started production in the late 1990s when better cold start emission control was needed to meet California's LEV2 standards. At the time only 12V electrical systems were available on vehicles, making the power demand to heat-up the EHC impractical, and as OEMs gained experience, the California and U.S. EPA standards were able to be met without catalyst heating as close-coupling the catalyst became the favored solution. Recently as 48V electrical systems were introduced in Europe, EHCs are being reconsidered and in fact EHCs have been applied to some passenger cars for thermal management. The recent shift to lower temperature combustion to achieve higher fuel economy has led to some discussion of further application of EHCs to the light-duty vehicle sector. As discussed in MECA's last white paper, heated dosing can be achieved by spraying urea solution onto an electrically-heated catalyst (EHC) (MECA, 2019). The EHC was briefly energized with 4 kWh of electric power to allow dosing at 180°C versus the normal dosing temperature of 200°C, resulting in FTP NOx emissions being reduced by 40% compared to the baseline close-coupled configuration. The adoption of 48-volt electrical systems to commercial vehicles can enable more efficient EHCs for thermal management, as well as heated dosing because the heat energy can be drawn more efficiently from the electrical system than from the engine. Furthermore, capturing and storing regenerative braking energy in the battery for heating up the EHC can result in a net-zero CO_2 impact from the active heating of the EHC.

Another key diesel engine component that is being considered for electrification in a 48-volt architecture is the exhaust gas recirculation (EGR) pump. An electrically driven EGR pump offers independent control of EGR rate decoupled from engine speed. This may be important in low speed operation where it was previously difficult or impossible to drive sufficient EGR flow for reducing engine-out NOx. Electrified EGR pumps also enable optimization of turbochargers independent of driving EGR flow, which can compete with turbo boost function. For example, a system that includes a high efficiency fixed geometry wastegate turbo and electrified EGR pump, can be optimized to minimize pumping work and thus improve fuel economy.

2.3.2 High Voltage Systems

A limitation of 48V mild hybrid systems is the total power available, with the latest systems offering a maximum of 30kW due to the need for suitable cabling. It is becoming increasingly common in Europe to find light-duty vehicles offering either hybrid or full electric drivetrain systems. Full hybrid configurations are currently found on several models of light-duty passenger cars and light trucks in the U.S. These include models that can also be plugged-in to enable some all electric operation, usually described as all-electric range (AER). A full hybrid can enable electrification of many of the components described above for mild hybrid vehicles, but the higher voltages allow for more parts to be electrified and to a larger degree. Full hybrids implement a larger electric motors and batteries, which support greater acceleration capability and regenerative braking power.

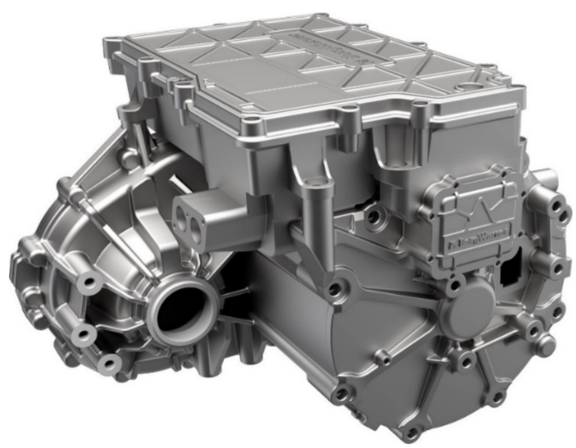

Figure 8. Integrated electric drivetrain module.

Mild hybridization is well-suited to heavy-duty vehicles used for long-haul transportation because of the limited fuel economy of a full hybrid at highway speeds. Full hybridization and electrification are more practical for small heavy-duty vehicles (e.g., Class 4-6) that do not travel long distances or operate for long periods of time without returning to a central location. Full hybrid vehicles have made the highest penetration into parcel delivery, beverage delivery and food distribution vehicles (CARB, 2015). We expect to see some application of strong hybrids combined with a low NOx engine to reduce CO_2 emissions in several vocational applications.

Integrated electric drivetrain systems (Figure 8), consisting of a fully qualified transmission, motor and power electronics controller, are now commercially available. With power levels of over 160kW and the ability to meet high torque requirements, these systems enable electrification of medium duty commercial vehicles. There are also an increasing number of electric drivetrain solutions up to 300kW that are suitable for Class 8 vehicles that can be used with either battery or fuel cell power sources.

3.0 Feasibility Demonstration of Achieving 0.02 g/bhp-hr NOx Emissions

Simulation models are a valuable design tool for technology developers during the design of engine components as well as catalyst exhaust systems because the design can be optimized without building full-size or even small-scale replicas for engine or reactor testing. To be effective, model simulations of fluid flow, exhaust flow or catalyst reaction mechanisms must be validated against actual component testing or engine-aged parts to ensure correlation with model assumptions. When a catalyst manufacturer is designing a system for a particular engine, they will input exhaust temperature, flow rates and engine-out exhaust chemistry into the models to decide on the specific size, architecture and catalyst chemistry that meets the necessary tailpipe emission limits. The models can also provide insight into how substrate volumes and catalyst loading can affect emissions over certification cycles.

MECA members that designed the exhaust configurations for the SwRI test program that would achieve a 0.02 g/ bhp-hr target over the FTP relied on their in-house proprietary models to figure out what catalyst technology would be appropriate. The results discussed in this section are based on applying these models to exhaust from the 2017 Cummins X15 engine retrofitted by SwRI with cylinder deactivation. The engine-out exhaust characteristics such as flow, temperature, and NOx level, among others, were provided by SwRI as inputs into the models. Finally, the benefit of heated dosing was demonstrated over both the FTP and the low load cycle (LLC-7) in testing conducted at SwRI (CARB, 2019).

3.1 Future Exhaust Emission Control Architectures

Similar to our previous white paper on 2024 engine standards (MECA, 2019), MECA conducted a study utilizing engine-out exhaust characteristics, from a modified engine calibration developed by SwRI, as an input to an emissions model for the purpose of simulating the emissions from fully aged exhaust aftertreatment systems. Two systems and several scenarios from the previous MY 2024 MECA white paper were modeled, including emissions from cold-start and hot-start FTP as well as low load cycles. As we discussed previously, we believe that even traditional system architectures, like System 1 below, can achieve an FTP limit of 0.05 g/ bhp-hr by 2024 through the combination of improved engine calibration, better catalysts and better controlled urea dosing. By 2027, OEMs will gain experience with heated dosing and dual SCR configurations and begin to incorporate engine and powertrain approaches to thermal management and CO_2 control to meet future tailpipe NOx standards as well as Phase 2 GHG limits. In this section we discuss incremental advancements such as the use of CDA, close-coupled SCR with dual urea dosing that some OEMs are already experimenting with in their laboratories (Cummins, Inc., 2018).

The system configurations employed in the model are shown in Figure 9 and include a traditional system layout consisting of a DOC, DPF and SCR (S1) and two advanced system layouts (S2 & S3) where additional SCR volume is brought closer to the engine to take advantage of passive thermal management using hotter engine exhaust. These system architectures demonstrate several options available to OEMs when designing exhaust controls for MY 2027 engines. System S1 has a similar configuration as current emission control systems but utilizes the latest generation of SCR catalysts, which are being offered today. System S2 is a twin SCR arrangement with front and rear SCR catalysts both in the underfloor location. This smaller, front SCR system, includes a second, typically heated, urea doser, SCR catalyst and ammonia slip catalyst (ASC), immediately upstream of the diesel oxidation catalyst, catalyzed DPF and downstream SCR/ASC with a conventional urea doser. This configuration may be slightly larger than S1 but still significantly smaller than original MY 2010 emission control systems. Finally, system S3 retains the twin SCR arrangement but brings the light-off SCR into a close-coupled position at the outlet of the turbocharger. Unlike S2, the front SCR and urea doser in S3 would most likely be installed in the engine compartment to take advantage of the hottest, turbine-out exhaust temperature.

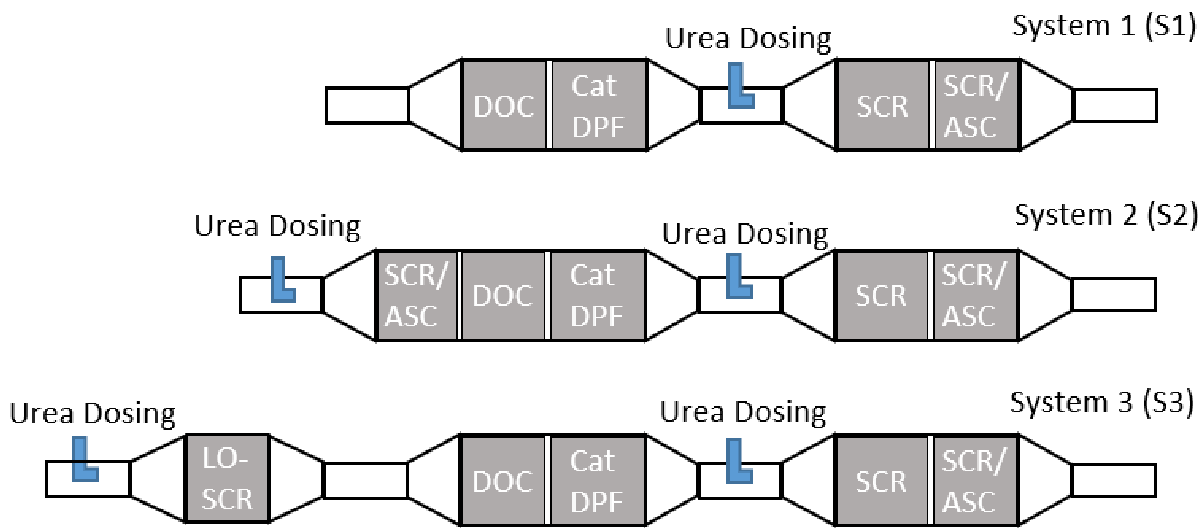

Figure 9. System configurations tested to demonstrate the feasibility of 2027 engine emissions. System S1 is based on 2019 engines in production today. System S2 employs a light-off SCR in a twin SCR arrangement. System S3 employs a dual SCR arrangement with a turbo-out close-coupled SCR upstream of a traditional underfloor system containing a DOC, DPF and second SCR.

3.2 Emissions Model Assumptions

An emissions model analysis was conducted using an improved engine calibration and advanced commercially available catalysts, including DOC, SCR and ASC, in the three aftertreatment design architectures shown in Figure 9. The model inputs include real engine out exhaust data, from a commercial engine with CDA that was calibrated by SwRI under the CARB Low-NOx Demonstration Program using an advanced cold start strategy. The CDA based thermal management enables rapid exhaust gas warm-up and low engine out NOx during cold start. The catalyst conversion parameters input into the model were derived from commercially available accelerated aged catalysts under conditions that represent the current full useful life requirement of 435,000 miles of operation.

The catalyst size represents an average system SCR volume found on today's trucks in the field. It is important to note that different engine manufacturers will specify SCR volume based on the engine-out NOx levels, engine calibration and deterioration factors expected over the useful life of the engine. Besides in-cylinder thermal management, the model assumes no additional active thermal management, such as additional fuel injected upstream of the DOC, and utilizes only the engine out temperature data provided by SwRI. Finally, the model assumes a single urea dosing strategy for the configuration S1 and dual urea dosing for configurations S2 and S3 (Figure 9). The dosing strategy for S1 was dependent upon exhaust gas temperature and started with minimal dosing at 150°C and full dosing by 185°C. Urea dosing below 185°C is assumed to be heated dosing to prevent urea deposits on the catalyst, mixer or exhaust system. The dosing strategy for S2 and S3 included heated dosing for the front SCR that initiated between 130-150°C and conventional dosing for the rear SCR. The front doser and SCR was only activated during low exhaust temperatures and the rear SCR was utilized in hot exhaust.

3.3 FTP Test Cycle Model Results

Figure 10 shows the predicted emissions from the three previously described emission control systems in Figure 9. The results of the analysis indicate that currently available catalysts employed at today's average catalyst volumes in advanced system configurations can achieve weighted composite FTP NOx emissions of less than 0.02 g/bhp-hr. In fact, the models predict that if today's underfloor system architectures (S1) utilized the latest commercially available catalysts with better urea dosing in combination with better engine calibration, they could achieve a composite FTP NOx emission rate equal to 0.02 g/bhp-hr. While this would be insufficient to allow for the necessary compliance margins that OEMs rely upon to ensure compliance over the useful life of a truck that can exceed a million miles, it shows the untapped emissions control performance available without making significant changes to current system designs. In addition, the model emissions from heavy-duty diesel engines are on par with natural gas engines currently available for similar heavy-duty vehicle classes.

The difference in performance of the three system architectures is not as pronounced over the FTP cycle compared to the LLC (see Section 3.4). There are two reasons for this. First, the catalysts in all system architectures are all highly efficient when the system is warmed up, as tested in the hot FTP, and hot FTP emissions are weighted as 6/7 in the composite FTP result with cold-FTP representing 1/7 of the weighting. Second, cold-start emission reduction is mainly accomplished by thermal management strategies either actively, at the engine, or passively, with exhaust insulation, and all system architectures can benefit from these improvements. Variability in results when modeling different systems can occur due to variation in catalyst formulation, and modeling assumptions. In the case of Figure 10, below, the differences between S2 and S3 are minor and most likely explained by model variability. The lowest modeled results reported here (0.014 – 0.016) allow for a compliance margin of roughly

25% at an FTP NOx emission standard of 0.02 g/bhp-hr. It should be noted that the modeled results shown here compare favorably with the preliminary engine test results from Stage 3 of the Low-NOx Test Program presented at the September 26, 2019 CARB workshop and reproduced in Figure 12 (Sharp, Update on Heavy-Duty Low NOx Demonstration Programs at SwRI, 2019).

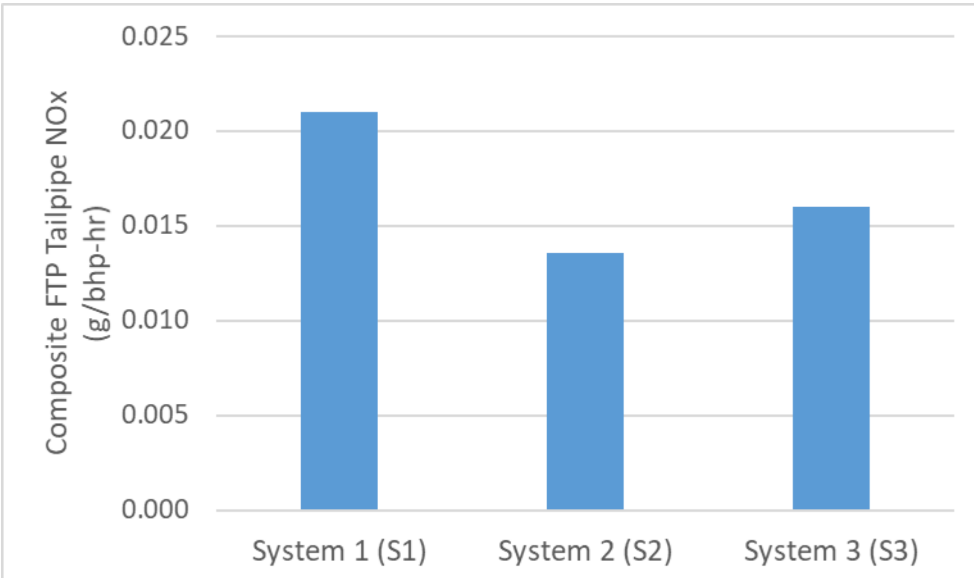

Figure 10. Modeled composite FTP NOx emissions from the latest generation commercially available catalysts employed in three different system architectures.

As noted in our white paper on MY 2024 technologies, advanced emission controls can be optimized to minimize N_2O emissions. Catalyst manufacturers can utilize a number of approaches to optimize exhaust emission controls for low N_2O emissions, including catalyst formulation, system design, engine plus aftertreatment calibration, and precise urea dosing control. Dynamometer testing showed the ability to simultaneously reduce NOx while maintaining N_2O levels below the federal cap of 0.1 g N_2O/bhp-hr (MECA, 2019). In addition, testing in the CARB Low-NOx Demonstration Program has shown N_2O levels are well below the federal cap when using twin SCR systems that also meet the NOx and CO_2 targets of the program, shown in Figure 12 below (Sharp, Update on Heavy-Duty Low NOx Demonstration Programs at SwRI, 2019). A benefit of twin SCR systems is the ability to simultaneously reduce NOx and N_2O through calibration and controls. This is because single SCR systems with the SCR downstream of a DOC benefit in NOx reduction due to NO_2 formed in the DOC, but this can come at a cost of increased N_2O formation. Dual SCR systems that partially reduce the engine out NOx before the NOx reaches the DOC will then make less N_2O over the downstream SCR, resulting in both high NOx conversion and reduced N_2O emissions. Controlling N_2O emissions is important because they are regulated in the Phase 2 GHG regulation and can be traded against CO_2 at a multiplier of 298 based on the GWP for N_2O when manufacturers over comply or exceed the cap.

3.4 Model Results During Low Speed and Load Operation

As CARB and EPA consider future low-NOx heavy-duty engine standards, both agencies have come to the realization that a new certification cycle must be developed to better represent real-world operating conditions experienced by vehicles that span multiple vocations and duty cycles. A recent analysis performed by the International Council on Clean Transportation (ICCT) analyzed the in-use test data from on-road trucks in Europe and the U.S. and showed that U.S. trucks were emitting NOx at approximately 50% higher levels than European trucks using very similar exhaust system configurations and volumes (Badshah, Posada, & Muncrief, 2019). Of course, the U.S. engines must comply with not-to-exceed (NTE) compliance testing focused primarily at high speeds, whereas the European engines are calibrated differently to comply with a moving average windows data analysis that also includes lower speed city driving. It is important to note that until recently, European trucks did not have to comply with CO_2 standards, and Europe still does not have an N_2O standard. The U.S. NTE requirements were established before emission controls such as SCR were implemented on trucks and the NTE was designed to control NOx emissions at highway speeds. Because the limitations of low-temperature NOx conversion by the SCR were not anticipated, U.S. engines were not calibrated to address NOx emissions in low load operation. As shown above, with improved calibration, current engines and the latest emission control technologies are able to achieve NOx emissions as low as 0.05 g/bhp-hr over the FTP certification cycle by 2024, allowing for sufficient compliance margin. However, in low load operation, today's engines likely require modified calibration and better thermal management, when the SCR cools below its catalyst light-off temperature.

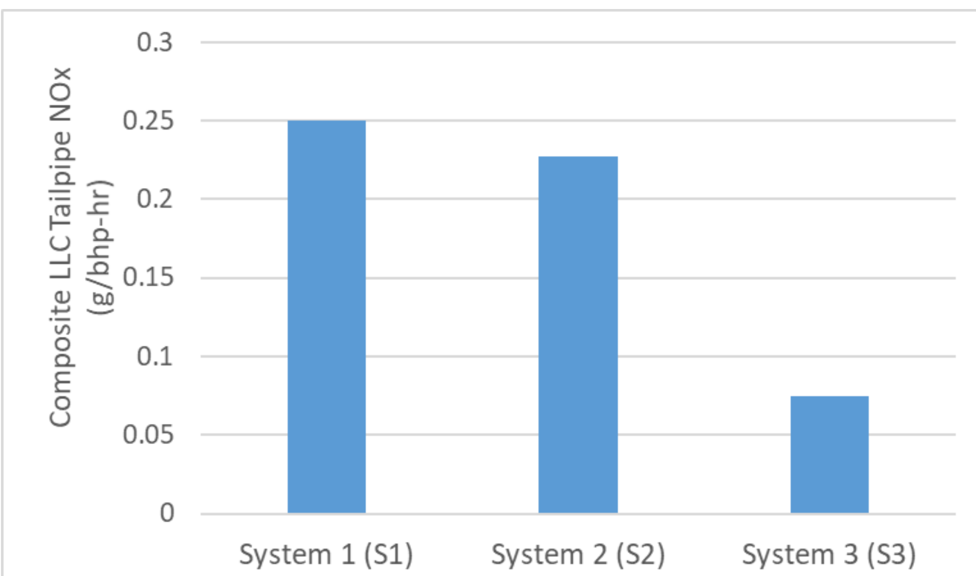

Figure 11. Modeled LLC NOx emissions from the latest generation commercially available catalysts employed in three different system architectures.

MECA modeled tailpipe NOx emissions from an engine with the three emission control architectures shown in Figure 9 over the LLC-7 cycle developed by SwRI and proposed by CARB (CARB, 2019). The same fully aged catalysts with industry-average SCR system volumes were modeled. The engine-out emission levels and exhaust temperatures over this cycle were provided by SwRI based on engine calibration with CDA to provide thermal management without the need for exhaust fuel dosing over the DOC, which would increase CO_2 emissions. As was the case for the FTP modeling above, the LLC modeling evaluated heated dosing for the front SCR in each twin SCR configuration when exhaust temperatures reached 130-150°C. As previously described in our 2024 NOx technology white paper, heated dosing delivers ammonia at lower temperatures so the SCR can initiate NOx conversion in colder exhaust than the typical 200℃ temperature for dosing initiation used on trucks today (MECA, 2019). Heated dosing also reduces the risk of urea deposit formation when using traditional dosing of urea at lower temperatures (MECA, 2019). Given recent discussions on the development of the LLC, the model assumed a preconditioning cycle of one hot FTP prior to running the LLC, as proposed by CARB. This is estimated to result in approximately a 20% ammonia pre-storage on the SCR catalyst. The results, shown in Figure 11, indicate that emission controls and close-coupled SCR architectures like S3 can achieve tailpipe NOx emissions down to 0.075 g/bhp-hr over the LLC. The significant reduction in NOx during low load and low speed operation is achieved by the close-coupled SCR in configuration S3 taking advantage of the higher turbine-out exhaust temperature.

3.5 Engine Test Results

As described previously, a test program to demonstrate the potential to meet low-NOx emission levels on current heavy-duty diesel engines has been underway at SwRI since 2015 (Sharp, Webb, Yoon, Carter, & Henry, 2017). Three stages of this test program were planned, and two have been completed on a MY2013 Euro VI calibrated engine equipped with turbocompounding. Stage 3 testing is utilizing a MY2017 non-turbocompound 15L engine and future exhaust system architectures like System 3 in Figure 9. Other engine technologies like CDA and EGR bypass were used to achieve the lowest possible NOx emissions while not increasing fuel consumption. Preliminary results from this stage of the test program support the modeling results presented in Sections 3.3 and 3.4 above. This is not surprising because the models, like those presented here, were utilized to make the most informed decisions on catalyst volumes, catalyst chemistry, configurations and dosing strategies to design the exhaust controls used for the CARB test program. As was previously stated with the modeled emission results, the engine test results confirm the ability of advanced diesel engines and aftertreatment to emit NOx at ultra-low levels on par with natural gas engines.

Figure 12 provides preliminary engine dynamometer results from an exhaust system aged in the laboratory to represent full useful life from Stage 3 of the CARB Low-NOx Demonstration Program as of the release of this report. A full engine-based accelerated aging is currently underway and will be published in the near future. As shown in Figure 12a, the composite FTP emission result at the tailpipe from engine testing of the lab aged exhaust system (0.019 g/bhp-hr) is comparable to the average modeled NOx emission of the System 3 (0.016 g/bhp-hr). OEMs will be able to utilize their calibration expertise to provide additional compliance margin below 0.02g/bhp-hr on the FTP cycle by 2027. It is most appropriate to compare the engine testing to the modeled results of System 3 because both include a close-coupled SCR catalyst and is the most comparable configuration to the aftertreatment system employed in the Stage 3 engine testing. Similarly, the LLC emission result at the tailpipe from engine testing (0.064 g/bhp-hr) is about 15% less than the modeled NOx emission result from System 3 (0.075 g/bhp-hr), primarily due to further calibration by SwRI to optimize emissions over the cycle. While not shown in the figure, it should be noted that SwRI also reported N_2O results for the Stage 3 system. These were well controlled at 0.065 g/bhp-hr, 0.05 g/bhp-hr and 0.05 g/bhp-hr for the composite FTP, RMC and LLC cycles. The N_2O cap required under the heavy-duty Phase 2 regulation is 0.1 g/bhp-hr.

a)

b)

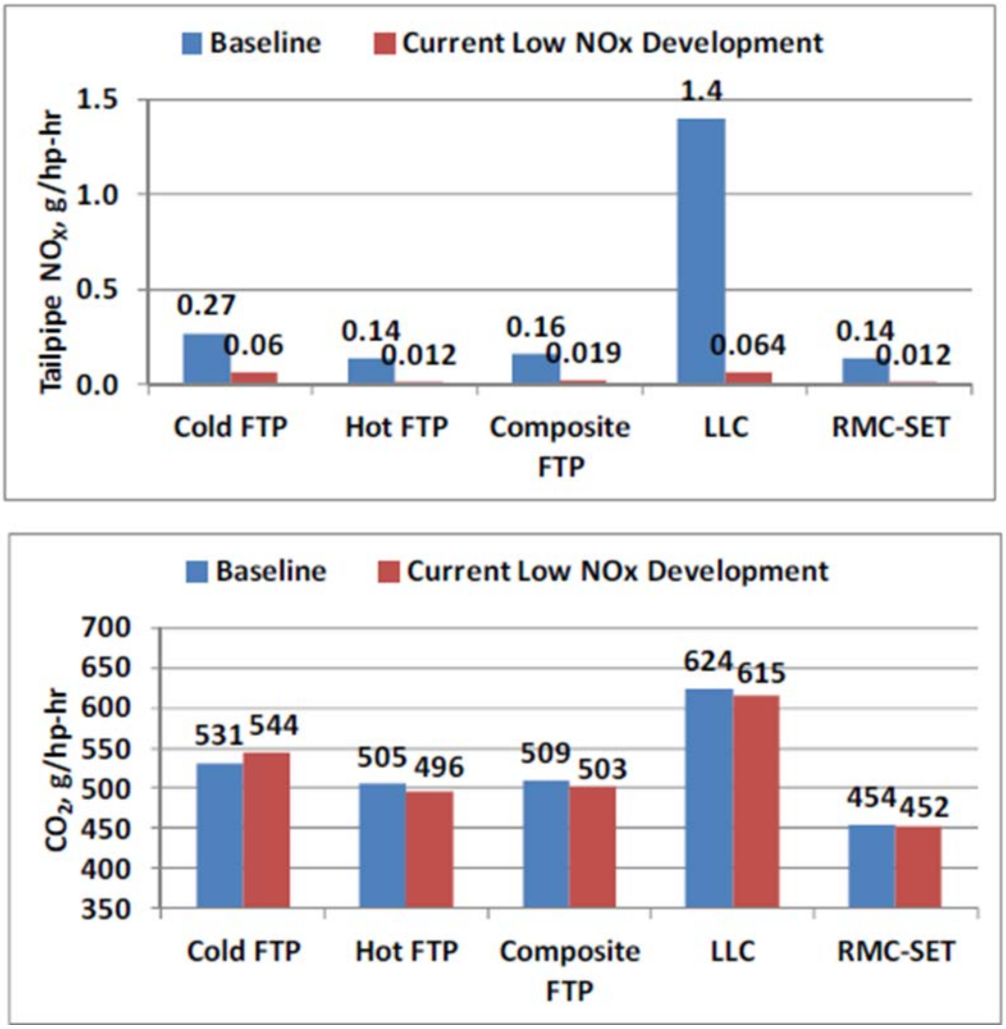

Figure 12. Emission Results for a) NOx; and b) CO2 from the Heavy-Duty Low-NOx Demonstration Program at SwRI (Sharp, Update on Heavy-Duty Low NOx Demonstration Programs at SwRI, 2019).

These engine results exhibit the importance of catalyst models in predicting exhaust emissions while also demonstrating the importance of engine calibration to fine tune the engine and aftertreatment system to exceed modeled predictions. Figure 12b confirms that not only can lower NOx limits below 0.02 g/bhp-hr over the FTP and 0.064 g/bhp-hr over the LLC be achieved, but they can be met with no net increase in fuel consumption. In fact, the utilization of cylinder deactivation as well as advanced engine calibrations results in a net fuel savings while delivering 90% lower NOx emissions. By 2027, OEMs and their suppliers will continue to improve engines by deploying CO_2 reducing technologies to meet future 2027 CO_2 emission limits.

3.6 Estimation of Aftertreatment System Costs

In support of cost-benefit analyses that will be conducted by CARB and U.S. EPA as part of the development of future heavy-duty NOx standards, MECA estimated the costs (in 2019$) of the technologies modeled in this report and hardware being tested at SwRI in the low-NOx program. The cost results were compiled by an independent third party to represent a range of costs for a full aftertreatment system. It is important to note that the hardware costs presented here represent only a part of the cost incurred by an OEM during the engine production process. The full NREL analysis is expected to be published in early 2020.

In our cost analysis, we first estimated a cost range of current heavy-duty emission controls systems having an architecture like System 1 in Figure 9. The costs were based on meeting today's FTP-limit of 0.2 g/bhp-hr over a useful life of 435,000 miles. The hardware included the DOC, DPF and SCR catalysts along with the DEF dosing system and OBD sensors and controllers necessary to comply with current OBD requirements. We estimated costs for two engine sizes, 6-7L and 12-13L. The former is often found in Class 4-6 heavy-duty vehicles while the latter is found in Class 7-8 vehicles. The cost estimate for a current aftertreatment system on a vehicle with a 6-7L engine is about $2,600 to $3,500. This is roughly 15%-38% less than that estimated by the ICCT ($4,152) in a 2016 cost study of similar systems produced five years ago (Posada, Chambliss, & Blumberg, 2016).

For a Class 8 line-haul tractor with a 12-13L engine, we estimate a cost of the engine and aftertreatment hardware to be in the range of $3,500 to $4,600 per truck. This is about 10%-30% less than that estimated by the ICCT in a 2016 cost study of similar systems produced five years ago. The ICCT report estimated the cost of a 2015 exhaust emission control system (not including EGR) in the U.S. or Europe was about $5,068 or 3% of the cost of the average retail truck price reported as $157,000 (Posada, Chambliss, & Blumberg, 2016). It is important to note that the average price of a heavy-duty line-haul truck has historically increased by about 1% per year (Posada, Chambliss, & Blumberg, 2016) due to safety, operational and other customer demanded enhancements that truck manufacturers have added to trucks. At the same time, emission control technology suppliers are typically expected to reduce the costs of their components through manufacturing improvements and other optimization by about 2-3% per year. The year-over-year supply chain reductions can account for much of the cost difference between our 2019 estimated range and that reported by ICCT in 2016 ($468 to $1,568). Given declining emission control system costs and the average price of a heavy-duty truck is reported to have increased by approximately $8,000 since 2015, the emission control system cost has become a smaller portion of the total truck price.

The second part of our analysis involved estimating the cost of meeting an FTP certification standard of 0.02 g/bhp-hr and proposed LLC certification standard in 2027 with an emission control system similar to System 3 in Figure 9. To meet these tighter standards, the technology evolution (discussed above and in our 2024 technology report) includes incremental improvements to substrates and catalysts as well as the addition of a close-coupled SCR and dual dosing system with one heated doser, additional NOx sensors and an ammonia sensor in an upgraded OBD system. In addition, this analysis assumed the use of CDA and an EGR cooler bypass system. All of these technologies are currently being demonstrated in the CARB Low-NOx Demonstration Program. Two cost estimates were prepared; one that assumed today's durability and warranty requirements, and one assuming longer durability and warranty requirements that were proposed by CARB as of the January 23, 2019 Workshop (CARB, 2019). These requirements were a 1 million mile useful life (FUL) and 800,000 mile warranty for class 8 and 550,000 mile FUL and 440,000 mile warranty for Class 4-7 starting in 2027. Since that time, CARB staff have revised the FUL and warranty proposal to both reduce the mileages and phase in the requirements in two steps starting in MY 2027 and further extending the requirements in MY 2031. For Class 8 vehicles, the requirements would be 600,000 miles FUL and 450,000 mile warranty in 2027 and 800,000 miles FUL and 600,000 mile warranty in 2031. Therefore, we expect the cost estimate for longer FUL and warranty provided below to represent a worst-case scenario when the final proposal is released. Recently, U.S. EPA signaled in the Cleaner Trucks Initiative Advanced Notice for Proposed Rule (ANPR) that they will consider longer useful life mileages for heavy-duty trucks based on average engine rebuild intervals.

For a vehicle with a 6-7 liter engine, the incremental hardware improvements needed to meet a 0.02 g/bhp-hr certification limit on the FTP cycle and future LLC standard at today's durability and warranty requirements were estimated to add about $1,300 to $1,800 to the cost of the engine efficiency and emission control technologies. For a Class 8 tractor with a 12-13 liter engine similar incremental improvements were estimated to add about $1,500 to $2,050 (less than 1.2%) to the cost of a MY 2027 truck, estimated to be approximately $177,000, based on a historical 1% annual rate of MSRP increase reported by ICCT.

For a 6-7 liter engine, the estimated incremental costs to meet the above durability and warranty requirements assumed to be implemented in MY 2027 (per the January 23, 2019 proposal) were $1,800 to $2,450. For a Class 8 tractor with 12-13 liter engine, these increased durability and warranty requirements were estimated to add $2,000 to $2,750 to the cost of the emission control and engine efficiency technologies. Therefore, the estimated total additional emission control cost in 2027, including a 0.02 g/bhp-hr FTP tailpipe limit, LLC limit, 1-million-mile durability requirement and 800,000 mile warranty, would be $3,100 to $4,250 for 6-7 liter engines and $3,550 to $4,800 for 12-13 liter engines. If a Class 8 truck with 12-13 liter engine is assumed to sell for an average price of $177,000 in 2027, based on the historical 1% annual rate of increase reported previously, the additional cost of emission controls on this truck will account for roughly 2-2.7% of the total vehicle price. It is important to note the cost estimate is based on the CARB January 23, 2019 proposal of 1 million mile FUL and 800,000 mile warranty which has been since reduced to 800,000 mile useful life and 600,000 mile warranty for a Class 8 truck.

4.0 Fuel Quality Considerations and Long-Term Catalyst Durability

In order to achieve reductions in harmful emissions from heavy-duty diesel engines, federal regulations were designed to allow for an engineered systems approach that combines advanced engine designs, advanced exhaust control technologies, and improved diesel fuel quality. In current diesel engine regulations, fuel quality requirements set a limit on the amount of sulfur allowed in fuel. The reason for this is two-fold; first, when sulfur is present in fuel that participates in combustion, the resulting emissions contain sulfur oxides (SOx) as well as sulfate particulate matter. Second, sulfur oxides are known compounds that reversibly affects the performance of precious metal and SCR catalysts found in diesel emission control components through a number of deactivation mechanisms. The current limit of 15 ppm sulfur in ultra-low sulfur diesel was established based on precious metal (PGM) in diesel catalyst. The PGM oxidizing function of the DOC and DPF can reversibly deactivate over time in the presence of sulfur. The DOC serves to oxidize NO_2 from the engine so it is in the proper oxidation state to be reduced by the SCR using ammonia as the reductant. Similarly, the PGM on the DOC, upstream of the SCR, oxidizes SO_2 to SO_3 which is a stronger poison for the SCR. Because it is positioned upstream of the DOC/DPF, the front SCR in Systems 2 and 3, is primarily exposed to SO_2 which is a less severe poison for the zeolite SCR catalyst.

Well established thermal sulfur removal strategies are employed to reverse the negative impacts of sulfur on these catalysts. Commercial DOCs begin to recover from sulfur poisoning between 350-600°C, depending on the catalyst design. SCR catalysts are generally tolerant to sulfur found in today's fuels; however, long term exposure may cause gradual deactivation via two potential poisoning mechanisms. A less often occurring mechanism is the irreversible reaction of sulfuric acid with the zeolite catalyst washcoat. More often, sulfur can chemisorb onto catalyst active sites and block further NOx reduction reaction from occurring at the active site. If recovery is necessary, copper zeolite SCRs show nearly full recovery at 500°C. The SCR catalyst downstream of the DPF is typically regenerated during the periodic high temperature excursion used to regenerate soot from the DPF.

As described above, an aftertreatment architecture likely to be employed to meet 2027 FTP and LLC standards will include a twin SCR arrangement with a close-coupled SCR that is upstream of today's aftertreatment systems. The close-coupled SCR will be mainly exposed to SO_2 rather than SO_3, the latter being a more severe poison. Research suggests that poisoning of the close-coupled SCR can be reversed by heating the catalyst to 500°C, which can be achieved through late post injection or other engine thermal management strategies, including cylinder deactivation. The durability of the close-coupled SCR will be demonstrated during the final stage of full-engine aging out to 435,000 equivalent miles specified in the SwRI low NOx test program.

Furthermore, EPA will be conducting accelerated aging and durability demonstration out to 800,000 mile equivalent useful life using a new aging protocol being developed with industry partners. The results of this program will help to inform about the long-term impacts of fuel sulfur on SCR catalysts. Aging experience from catalyst manufacturers suggests that the greatest impact will be on the close-coupled SCR since this is closest to the engine and sees the highest temperature and the major portion of sulfur oxide exposure. The downstream, underfloor SCR is somewhat protected by the DOC and DPF and therefore will be the least impacted by fuel sulfur.

Some metals found in engine oils can also result in deterioration in catalyst performance. Lube oil phosphorus is a non-selective poison that effectively masks surface active catalyst sites, independent of the type of catalyst formulation. Generally, phosphorus deposits heavily at the front end of the catalyst brick, and typically resides mostly on the surface of the washcoat. There is some concern that phosphorus could react with other poisons and a catalyst washcoat to form phosphates that persist on the washcoat surface and mask the catalyst sites (Bunting, More, Lewis, & Toops, 2004). More research is needed here to determine the durability requirements to meet future full useful life provisions. Possible mitigation actions included increasing catalyst volume and/or inclusion of poison-resistant catalyst designs.

Other metals that are found in some fuels and oils, such as biodiesel, include calcium, sodium, potassium and magnesium. Calcium deposits uniformly across the catalyst and can physically block active sites. Elevated levels of sodium and potassium could displace the active metals and reduce the NOx conversion and N_2 selectivity. At this time, MECA is not aware of any data that shows that magnesium has a negative effect on catalyst performance. Recent research has shown how biodiesel metal contaminants can affect emission control systems (Williams, et al., 2011) (Lance, et al., 2016). Extensive testing of light-duty and heavy-duty aftertreatment systems exposed to biodiesel at the 10-ppm metal impurity specification for biodiesel has been published by NREL with funding from the National Biodiesel Board and support from MECA. A medium-duty pick-up truck aftertreatment system equipped with a front-SCR was aged out to 150,000 accelerated miles on fuel doped with metals to the current maximum specification and met the FTP emission limit for that vehicle (Williams, et al., 2014). Similarly, in a later study, a heavy-duty 2010 style aftertreatment system architecture like that represented by System 1 in Figure 9, was aged in an accelerated fashion to represent 435,000 equivalent miles of thermal aging using a similar doped biodiesel fuel and met the FTP emission limit after aging (Lance, et al., 2016).

Catalyst suppliers that have access to field aged exhaust aftertreatment systems beyond 435K are trying to assess longer term system durability beyond today's FUL. Limited testing from several high use trucks suggests that the aftertreatment systems are capable of meeting current emission standards with 95% NOx conversion after approximately 700,000 miles of real-world operation. Future systems will need to meet more stringent NOx emissions for longer specified mileage, and the durability impacts of commercial fuels will need to be further evaluated. As reported in the ANPR for the Cleaner Trucks Initiative, EPA has initiated a test program to develop an accelerated aftertreatment durability protocol that would allow the testing of aftertreatment systems out beyond today's useful life.

5.0 Conclusions

EPA and CARB have announced rulemakings focused on revising the heavy-duty truck emission standards, with a particular focus on tighter limits for NOx in the 2024-2027 timeframe. This report is a companion to a report released by MECA on June 10, 2019, in which we provided our assessment of technologies being commercialized by component suppliers, including MECA members, to help their customers comply with a future NOx standard of 0.05 gram/brake horsepower-hour (g/bhp-hr) on the heavy-duty FTP for model years (MY) 2024-2026. In this report, MECA presented cost-effective technologies being commercialized by suppliers for heavy-duty on-road engines that reduce both NOx and CO2 emissions. Test results from full useful life aged systems representing commercial or market ready technology options that can be integrated on vehicles by model year 2027 were shown to achieve 0.02 g/bhp-hr on the heavy-duty FTP certification cycle and approximately 0.075 g/bhp-hr in low load operation using the proposed low load certification cycle.

A variety of technology options can be deployed on heavy-duty engines and vehicles to reduce engine-out NOx while improving fuel economy to reduce the total cost of ownership of trucks. On-engine technologies and strategies that OEMs may choose to deploy to meet both a NOx and CO_2 standard in 2027 have grown dramatically in recent years as a result of the Phase 2 GHG regulation. These strategies can be deployed to address cold-start or low load operation to heat up aftertreatment and keep it hot under all engine operating loads. Once implemented, these technologies will help to pay for themselves by delivering fuel savings to truck owners.

Strategies for reducing emissions during low temperature operation, combined with improved engine calibration, thermal management and control of urea dosing, can be applied to heavy-duty trucks by 2027 to enable emission control systems to achieve an FTP NOx emission limit of 0.02 g/bhp-hr while maintaining low N_2O emissions. Greater compliance margins can be achieved through modest increases in catalyst volume, while still maintaining the size of future emission controls below those on model year 2010 trucks. The approaches discussed for meeting 2027 NOx limits utilize well understood aftertreatment system designs employing evolutionary improvements in technologies that have been developed over the past 17 years of experience with both light- and heavy-duty NOx regulations. Modeling and engine testing shows that engines with CDA combined with low temperature ammonia delivery through the use of heated urea dosing and closed loop, NOx and ammonia sensor-based control, on fully-aged commercial aftertreatment systems can achieve NOx emission below 0.075 g/bhp-hr over low-load, low-speed operation. We estimated the incremental cost of emission controls to achieve these low-NOx emission limits in MY 2027 to be between $1,500 and $2,050 on a Class 8, line haul truck estimated to cost about $177,000 in 2027.

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