TECHNOLOGY FEASIBILITY FOR MODEL YEAR 2024 HEAVY-DUTY DIESEL VEHICLES IN MEETING LOWER NOx STANDARDS

June 2019

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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.

In this report, MECA provides our assessment of technologies being commercialized by component suppliers, including MECA members, to help their customers comply with future lower NOx standards. 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 model year (MY) 2024 without significant changes to today's engines or aftertreatment. 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 2024 to achieve 0.05 gram per brake horsepower hour (g/bhp-hr) on the heavy-duty FTP certification cycle and approximately 0.2 g/bhp-hr in low load operation using the proposed low load certification cycle being developed at Southwest Research Institute under a contract from CARB. It is important to state that there are several technology paths to achieve these levels of emissions, and some of them can simultaneously lower greenhouse gas emissions, such that the NOx reductions do not compete with the CO_2 reductions.

The following assessment is based on the implementation timeline presented by CARB staff at the January 23, 2019 public workshop as well as the assumptions laid out in the CARB staff white paper released on April 18, 2019 (CARB, 2019). In the latter, CARB staff signaled a plan to align the regulatory provisions for the first phase of NOx tightening with the second 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 2024. 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 a 10% low power exclusion, similar to that required under Euro VI-D. Finally, the technologies considered in this assessment are assumed to be designed to meet a 435,000 mile full-useful life (FUL) and a 350,000 mile or 5 year warranty, with the latter going into effect in 2022 in California.

The conclusions in this paper can be summarized as follows:

1. **Compared to emission controls on MY 2010 U.S. diesel trucks, today's compact aftertreatment systems are 40% lighter, 60% smaller, and substantially less expensive.**

Manufacturers continue to optimize diesel emission controls, such as DOC, DPF and SCR, in order to promote uniform catalyst coating, improve NOx conversion efficiency, reduce back pressure on the engine, and reduce thermal mass. New substrates are designed with thinner walls or higher porosity, which allows the coating of better catalysts without sacrificing durability. This has resulted in higher catalyst loading per volume of substrate and led to downsizing of systems from those available in 2010. Furthermore, catalyst development has produced higher activity catalysts that can provide higher NOx conversion with lower catalyst loading. While the cost of new heavy-duty trucks has increased at approximately 1% per year, the cost of emission controls has come down, representing a lower percentage of the cost of a new truck. These advances have brought higher compliance margins and lower certification levels while still meeting future GHG standards. Advanced catalysts and substrates combined with better engine and urea dosing calibration can be readily employed to meet tighter NOx limits in 2024 without any significant changes to today's system design. Based on a survey of MECA's members, we estimate the cost of emission controls on a future ultra-low NOx truck to be similar to the cost of emission controls on a MY 2010 truck.

2. **Several vocational engine families have demonstrated the capability of achieving NOx emissions 50-75% below today's standards, while also meeting future heavy-duty greenhouse gas limits for vocational engines.**

Since 2010, setting stringent emission targets for both CO_2 and NOx through realistic regulations and expanding the calibrator's tool box from the engine to the powertrain has allowed engineers to achieve simultaneous NOx reductions and engine efficiency improvements. A review of EPA's heavy-duty certification tables (U.S. EPA, 2019) indicates that a number of diesel engine families certified since 2010 have shown the ability to achieve 0.1 g/bhp-hr and lower tailpipe NOx levels over the composite FTP certification cycle. Of those engines, several have demonstrated the ability to meet future Phase 2 GHG regulation limits for vocational engines that go into effect in 2021, 2024 and 2027. History has shown that once emission control and efficiency improving technologies were required on engines, the traditional trade-off relationship between CO_2 and NOx emissions at the tailpipe has been overcome and reductions of both pollutants could be achieved simultaneously.

3. **A wide 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.**

The number of on-engine technology options and strategies that OEMs may choose to deploy to meet both a 2024 NOx standard and the 2024 CO_2 standard has grown dramatically in recent years, as a result of the Phase 2 GHG regulation. Technologies such as cylinder deactivation (CDA), high efficiency variable geometry turbochargers with exhaust gas by-pass, and start-stop systems are only some of the commercially available fuel saving technologies that can be implemented by 2024. Some of these strategies can be deployed on cold-start to heat up aftertreatment and keep it hot under low engine load operation. Other technologies that are being demonstrated on vehicles include 48V electrical architectures combined with regenerative braking and small batteries that can electrify auxiliary components on the engines such as air conditioning compressors, water and oil pumps, EGR pumps, electric assist turbochargers, electrically heated catalysts, 48V motor-generators, 48V electric fans and auxiliary power units to take the load off the engines. Technologies like CDA and 48V mild hybridization can enable simultaneous NOx and CO_2 reduction, and once implemented, these technologies will deliver fuel savings to truck owners.

4. **Strategies for reducing emissions during periods of low load operation, combined with improved engine calibration and control of urea dosing, can be applied to heavy-duty trucks by 2024 to enable emission control systems to achieve an FTP emission limit of 0.05 g/bhp-hr and a Low Load Cycle (LLC) limit below 0.2 g/bhp-hr.**

Engine calibration and thermal management combined with advanced catalysts and substrates have improved to the point where a current engine plus aftertreatment system can achieve FTP emissions below 0.05 g/bhp-hr NOx with compliance margins that OEMs need for full useful life durability. During cold-start and low-load operation, engine calibration and thermal management, including the technologies listed in (3) above, can be applied to reduce engine out NOx emissions and provide additional heat to aftertreatment systems. Better catalysts and urea dosing systems can achieve high NOx conversion during lower temperature operation. Further 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. Some engine manufacturers may choose to include a light-off SCR catalyst before the DOC in a twin SCR system arrangement with dual urea dosing, to gain experience with the types of strategies that may be needed for lower NOx limits in 2027. The approaches discussed for meeting 2024 NOx limits utilize improvements in thermal management and engine calibration, and existing aftertreatment system designs that employ newer high efficiency catalysts and coating strategies. Simulations of commercial catalysts over a low load cycle show that low temperature ammonia delivery through the use of heated urea dosing can deliver NOx emissions below 0.2 g/bhp-hr over the LLC, representing extended low-speed operation and idling.

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) technology. However, current engines continue to be challenged 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). Furthermore, as noted above, hundreds of millions of people in the U.S. and around the world still breathe unhealthy air. This paper presents recent advancements in NOx emission control technology found on light-duty vehicles that could be implemented on engines used in commercial vehicles to reduce NOx to ultra-low levels. This paper particularly focuses on the feasibility of heavy-duty engines to achieve 0.05 g/bhp-hr on the FTP cycle and 0.2 g/bhp-hr in low load operation by MY 2024.

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 study 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 reductions can be achieved with an approximate cost effectiveness from $1,000 to $5,000 per ton of NOx reduced. We used a cost effectiveness methodology that is based on both certification emission levels as well as in-use emissions 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 vehicle's current full useful life of 435,000 miles. The resulting range of cost effectiveness values is due to variability in vehicle and engine characteristics. For example, turning over a higher-emitting vehicle that operates more frequently and lasts longer on the road will be more cost effective than a lower-emitting vehicle that operates for less time. EPA's estimate of $2,000 per ton NOx reduced for the 2010 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 $2000-$21,000 per ton (U.S. EPA, 2017). Similarly, CARB estimated the cost effectiveness for future low-NOx requirements to be approximately $6000 per ton (CARB, 2019).

2.0 Overview of NOx Control Technologies

There are two pathways to reduce NOx from internal combustion engines: improving combustion characteristics inside the engine and reducing exhaust emissions. Improvements in combustion characteristics are progressing through new types of combustion strategies, advanced piston designs, high pressure piezoelectric fuel injection, cooled exhaust gas recirculation (EGR) systems, variable geometry turbochargers, cylinder deactivation, variable valve lift and timing, among others.

At the same time, emission control manufacturers have continued to improve exhaust emission reduction technologies including substrates, catalysts, passive thermal management strategies such as insulated dual wall manifolds, and urea dosing and mixing approaches that more efficiently reduce exhaust NOx emissions. On today's vehicles, reducing tailpipe NOx emissions is accomplished primarily through the use of cooled EGR and SCR. EGR systems have advanced significantly since the technology's early introduction, through innovations such as floating core designs and other modifications to reduce fouling issues and improve durability. SCR catalysts for heavy-duty on-road trucks in the U.S. are primarily based on zeolites containing some amount of base metal catalysts, typically copper or iron.

The catalytic reduction of NOx over SCR catalysts requires the use of a reductant such as ammonia, which can be delivered as a gas or atomized aqueous urea solution (known as diesel exhaust fluid or DEF) that is converted to ammonia in hot exhaust. Typically, exhaust temperatures at which urea is sprayed into exhaust are above 200°C. However, advances in low temperature catalyst performance, liquid atomization and heated dosing have brought urea injection temperatures down as low as 130°C. Modern SCR system designs combine highly controlled DEF injection hardware and flow mixing devices for effective DEF-to-ammonia conversion and distribution of the ammonia across the available catalyst cross-section.

In addition to durable advanced SCR catalysts that are coated onto honeycomb ceramic substrates, today's emission control systems include ammonia slip clean-up catalysts that are capable of achieving and maintaining high NOx conversion efficiencies, low nitrous oxide (N_2O) formation with extremely low levels of exhaust outlet ammonia concentrations over thousands of hours of operation. Furthermore, catalyst manufacturers have developed more advanced methods to coat substrates in layered structures with different functionality or zoned with different catalysts on a single substrate to reduce system size and thermal mass. The evolution that has occurred in the catalyst industry over the past ten years since SCR catalysts were first installed on diesel engines has focused on improved low temperature NOx reduction and increased durability.

Manufacturers continue to improve SCR substrates in order to increase geometric surface area, allow uniform catalyst coating, reduce back pressure on the engine, and reduce thermal mass. Figure 1 shows how emission controls on heavy-duty trucks have evolved over the decade of implementation. As OEMs gained experience with engine calibration, catalyst suppliers made improvements to the performance and reduced manufacturing costs. More efficient packaging for thermal management and efficient urea mixing designs have allowed the systems to be reduced in size by over 60% while achieving lower NOx emissions than first generation systems. The cost of a heavy-duty truck has increased at approximately 1% per year (Posada, Chambliss, & Blumberg, 2016) while the cost of emission controls has declined, making emission controls a smaller fraction of new truck cost. Due to the combination of cost savings realized since 2010, as well as the cost reductions expected before new standards are implemented in 2024 and 2027, we estimate that the emission controls needed to meet future 0.02 g/bhp-hr standards in 2027 will cost about the same or less than MY 2010 systems.

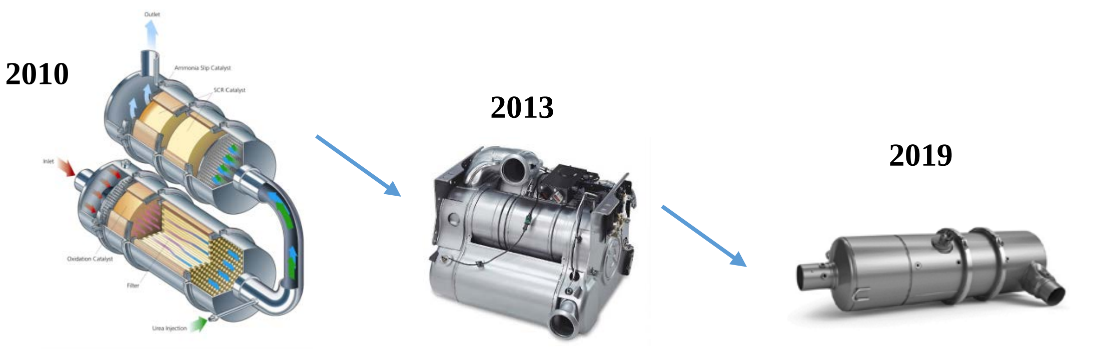


Figure 1. Evolution of heavy-duty emission control technology from 2010-2019.

The evolutions that have enabled system downsizing to occur over the past 10 years include new substrates with thinner walls and higher porosity, which allow for lighter systems with reduced constriction on the exhaust flow, leading to improved fuel economy. Research has demonstrated that advanced high porosity substrates can be coated to higher catalyst loading, facilitating size reduction of conventional SCR systems by as much as 50%. These new substrates allow catalysts to be deposited into pores of the honeycomb body, which in turn opens up the channels to lower pressure drop with the same catalyst loading. Lower back pressure on the engine improves fuel economy and reduces CO_2 emissions. An alternate approach to downsizing may be to increase the catalyst loading at the same pressure drop and reduce NOx emissions. Figure 2 shows an illustration and micrographs of the advanced versus conventional substrates (Tanner, et al., 2015).

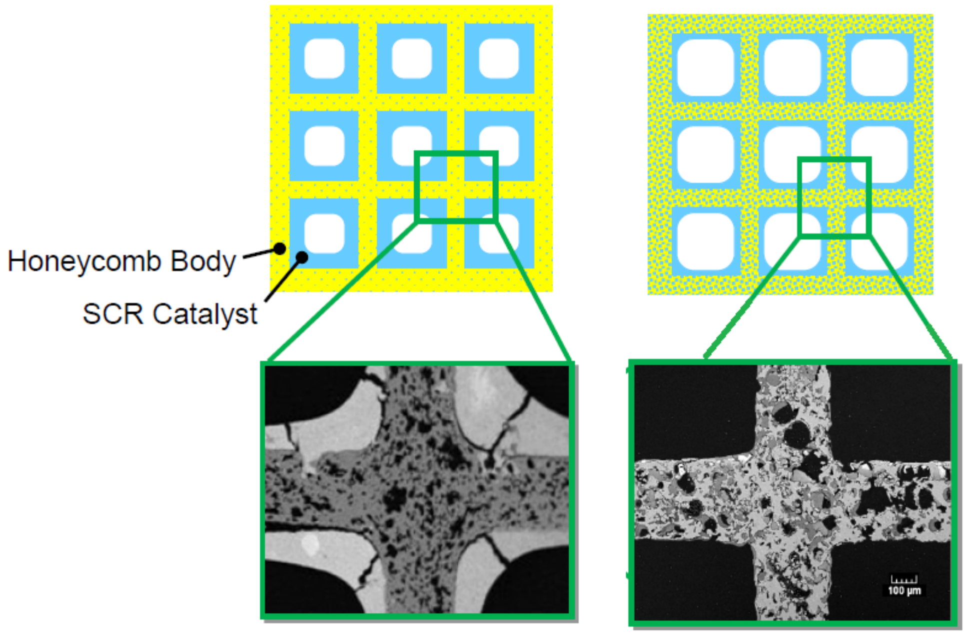
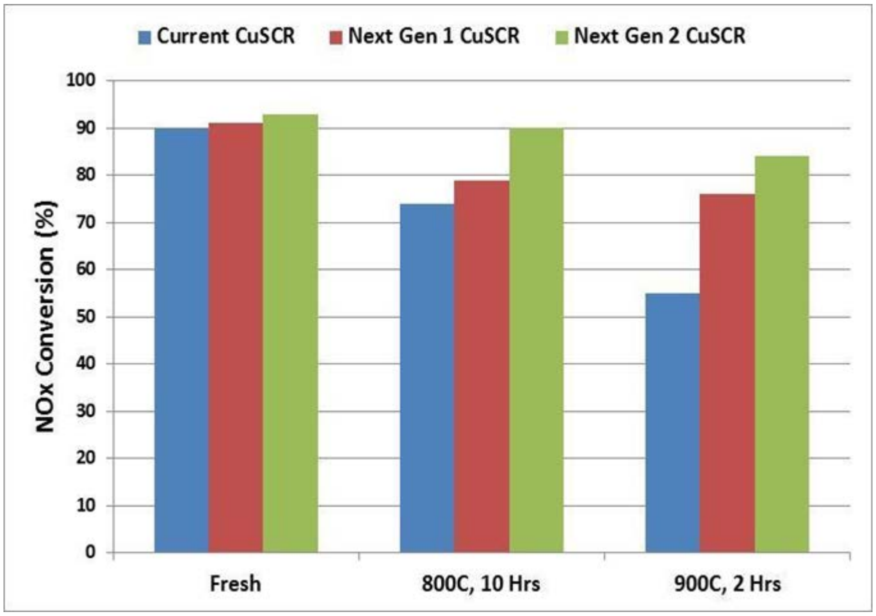
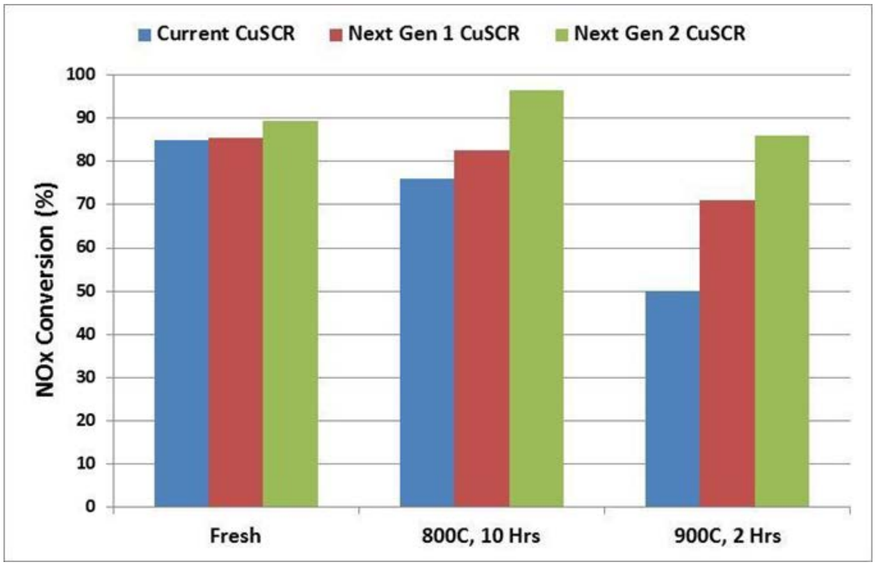


Figure 2. Comparison of a standard substrate (left) with an advanced high porosity substrate (right).

Catalyst manufacturers have continually improved SCR performance by focusing on low and high temperature activity to broaden the overall window of operation. Figure 3 demonstrates the advances in catalyst conversion and durability that have been made with advanced Cu-SCR catalysts (Walker, 2016). Fresh catalyst activity has increased with successive generations, and new catalyst formulations are retaining high conversion rates after aging at 800°C and 900°C. Higher activity catalysts have resulted in overall system downsizing and cost savings. Figure 3a shows low temperature NOx conversion efficiency measured at 200°C and Figure 3b shows the same catalysts tested at high temperature (600°C). Furthermore, catalyst durability has been a continued focus of research and development and will play an important role in future emission controls as regulations are expected to increase durability requirements. For example, the performance of the second generation Cu-SCR declined by less than 10% after aging at high temperatures. This is in contrast to earlier Cu-SCR systems that saw performance deterioration of approximately 40% under the same aging conditions. In addition, low-temperature NOx conversion by the latest advanced catalyst systems can be further improved with increased catalyst loading. Figure 4 shows the increase in NOx conversion, especially at low temperatures, when catalyst loading is increased from L1 to L2.



200°C



600°C

Figure 3. Demonstration of copper zeolite-based catalyst improvement at fresh and aged conditions. Three catalyst formulations are shown: a current version and two successive generations of catalysts. 3a) Exhaust temperature 200°C; 3b) Exhaust temperature 600°C.

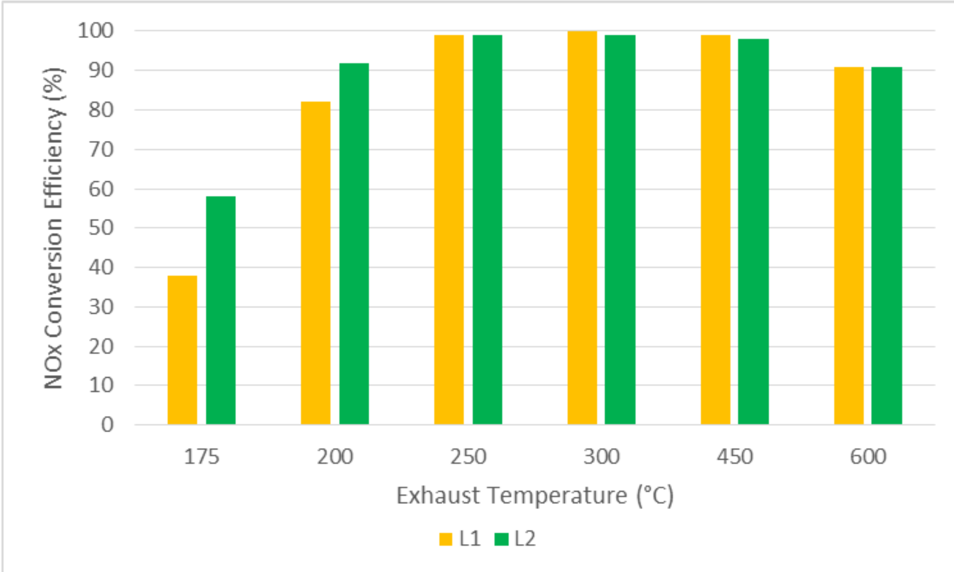


Figure 4. Impact of catalyst loading on NOx conversion efficiency. Test conditions were 1000 ppm NO only, ammonia-to-NOx ratio (ANR) of 1 and space velocity of 120,000/hr.

2.1 Control of Nitrous Oxide (N_2O)

While total N_2O concentrations in the exhaust are much lower than CO_2 concentrations, N_2O is approximately 298 times more powerful than CO_2 at trapping heat in the atmosphere. N_2O is emitted directly from motor vehicles and its formation is highly dependent on temperature, NO_2 to NOx ratio entering the SCR catalyst, ammonia-to-NOx ratio, the SCR catalyst formulation and the temperature of the catalyst during operation. Advanced gasoline and diesel powertrains for medium- and heavy-duty vehicles in conjunction with advanced emission control technologies 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.

At low temperatures, around 250°C, the predominant mechanism for N_2O formation is by the decomposition of ammonium nitrate, whereas at high temperatures, above 500°C, the primary mechanism is ammonia oxidation. Nitrous oxide can form at intermediate temperatures (300-350°C) if the NO_2 to NOx ratio exceeds 50%. Excess ammonia injection across the SCR catalyst can also lead to an increase in N_2O formation if the ammonia-to-NOx ratio exceeds 1.0. Test cycle, cycle exhaust temperature, system design and urea injection calibration all play a role in the formation of N_2O on the SCR catalyst (Hallstrom, Voss, & Sandip, 2013).

Catalyst formulation is an effective method to control N_2O emissions. Research has found that innovative catalyst chemistry in SCR systems can be effective at lowering N_2O while enhancing catalyst durability (Jansson, et al., 2015). System design can impact the overall NOx performance and N_2O emissions as a result of the average temperature of the SCR catalyst in each configuration relative to the optimal temperature for N_2O formation. Upstream components such as the DOC and DPF can also impact the N_2O levels based on their relative activity to form higher NO_2/NOx ratio feedgas to the SCR. Precious metal composition and loading can be formulated on the DOC and DPF to minimize their contribution to N_2O formation while still maintaining high NOx conversion efficiency. For all SCR systems, the N_2O emissions could be reduced by tighter urea dosing control to limit excess ammonia, by targeting an optimal amount of ammonia storage in the SCR catalyst.

SCR catalyst architecture can be designed to target lower N_2O emissions from the system (Kumar, Kamasamudram, Currier, & Yezerets, 2015). Since the front part of the SCR substrate is more prone to form N_2O, it is possible to zone coat the front of the substrate with catalysts that do not favor N_2O formation. Further optimization has been demonstrated with the latest catalyst technology installed on recent model year engines. Testing showed that N_2O emissions of 0.015 g/bhp-hr can be achieved, which is well below the regulated cap of 0.100 g/bhp-hr (Figure 10).

U.S. EPA considered lowering the N_2O limit to 0.050 g/bhp-hr in the Phase 2 GHG regulation. However, the agency ultimately decided to leave the limit at 0.100 g/bhp-hr in order to allow OEMs more flexibility to meet current CO_2 standards and potential future NOx standards. EPA noted its intention to revisit the standard at a later date to further control N_2O emission, as part of a future rule to consider more stringent NOx standards. Advanced SCR and ammonia slip catalysts are able to achieve lower N_2O emissions that manufacturers can use to trade-off for CO_2, and comply with future GHG standards using a warming potential for N_2O that is 298 times greater than CO_2.

3.0 Assessment of the Capabilities of Today's Engines and Aftertreatment

The calibration of internal combustion engines is a delicate balance that has to deal with trade-offs to optimize performance and emissions. For example, there is an inverse relationship between PM and NOx emissions that engine manufacturers applied to meet emission standards up through the 2006 heavy-duty highway regulations. In 2007, the requirement to reduce both PM and NOx emissions caused OEMs to install diesel particulate filters (DPF) on diesel vehicles, which allowed engine calibrators to optimize the combustion in the engine to meet lower NOx emissions while relying on the DPF to remediate the resulting higher PM emissions. This example of effective emission regulations provided a technology solution to overcome the traditional barriers of engine calibration. In 2010, SCR systems were installed on most trucks in response to a further tightening of NOx limits. SCR allowed calibrators to not only reduce the soot load on DPFs (and in turn provide a better NOx to soot ratio to promote passive soot regeneration) as a way of improving fuel efficiency but also to take advantage of another well-known trade-off in combustion thermodynamics between fuel consumption (or CO_2 emissions) and NOx emissions from the engine.

Since 2010 the predominant technology to reduce tailpipe NOx from diesel engines has been SCR, and every generation of SCR systems has led to improvements in catalyst conversion efficiency. In 2011, EPA adopted federal GHG standards for heavy-duty trucks that were implemented in 2014 through 2020. The Phase 2 regulation was adopted in 2016 to cover trucks from 2021 through 2027. Engine manufacturers quickly recognized SCR as a very effective technology option that has allowed them to meet the first phase of heavy-duty GHG standards while still achieving NOx and PM reduction targets from the engine. OEMs have accomplished this by calibrating new engines to burn less fuel and rely on the SCR system to remediate the additional NOx emissions that result from such calibration.

The portfolio of technology options available to reduce GHG emissions from heavy-duty trucks and engines is continually growing in response to federal GHG standards. In fact, a review of heavy-duty engine certifications from 2002 to 2019 shows that once emission control and efficiency improving technologies were required on engines, the inverse relationship between CO_2 and NOx emissions at the tailpipe was overcome and both were reduced (see Figure 5 below). By setting stringent emission targets for both CO_2 and NOx through realistic regulations, calibrators have expanded their tool box from the engine to the powertrain to enable simultaneous NOx reductions and engine efficiency improvements.

Figure 5 plots the past 17 years of EPA certification data for NOx and CO_2 for heavy-duty engines tested on the FTP cycle. Several engines certified since 2010 have shown the ability to achieve 0.1 g/bhp-hr or lower NOx emissions over the composite FTP certification cycle, which is 50% below the current standard. Of those engines, several have demonstrated the ability to meet future Phase 2 GHG regulation limits for vocational engines that go into effect in 2021, 2024 and 2027. For example, the MY 2017 Detroit Diesel DD13 reported 0.06 g/bhp-hr NOx and 496 g/bhp-hr CO_2 on the FTP cycle. The Phase 2 GHG regulation vocational engine standard for a MY 2027 heavy-heavy engine is 503 g/bhp-hr CO_2. It is important to mention that these reported certification emission test results are not the standards to which the engine is certified, but are the reported emissions results from fully aged aftertreatment during certification testing. The manufacturers maintain the difference between the reported test results and the standards as a compliance margin, which ranges between 20-50% depending on the manufacturer, in order to account for changes to emissions performance over time due to real world operation and deterioration.

It must be noted that the Phase 2 GHG regulation was designed such that the engine must meet one standard if used in a vocational application and a more stringent set of standards if used in a line-haul tractor application. In contrast to the MY 2027 vocational engine standard described above, the line-haul tractor standard for MY 2027 and later heavy-heavy engines is 432 g/bhp-hr CO_2. To demonstrate compliance with the Phase 2 GHG regulation line-haul tractor standard, OEMs must report CO_2 test data from the ramped modal cycle (RMC) and use weightings for each mode that are specific to Phase 2 (and different than the weightings for Phase 1). The same DD13 engine mentioned above, when certified over the Ramped Modal Cycle emits 447 g/bhp-hr CO_2, and it will need an additional 3.5% CO_2 reduction to comply in 2027. Unfortunately, there is no publicly available Phase 2 weighted RMC data for these engines at this time and therefore the values in Figure 5 represent NOx and CO_2 measurements over the heavy-duty FTP test cycle. As a point of reference, most line haul truck engines in production today are just meeting the 2017-2020 CO_2 limit, which offers an opportunity to deploy a number of readily available efficiency technologies, such as cylinder deactivation or engine-off coasting to meet the Phase 2 GHG regulation requirements, while reducing low-load NOx emissions. The next section of this paper describes the types of technologies available to

OEMs to simultaneously reduce NOx and CO_2 emissions to comply with Phase 2 GHG regulation requirements and a forthcoming low-NOx engine standard for both vocational engines and line-haul tractor engines.

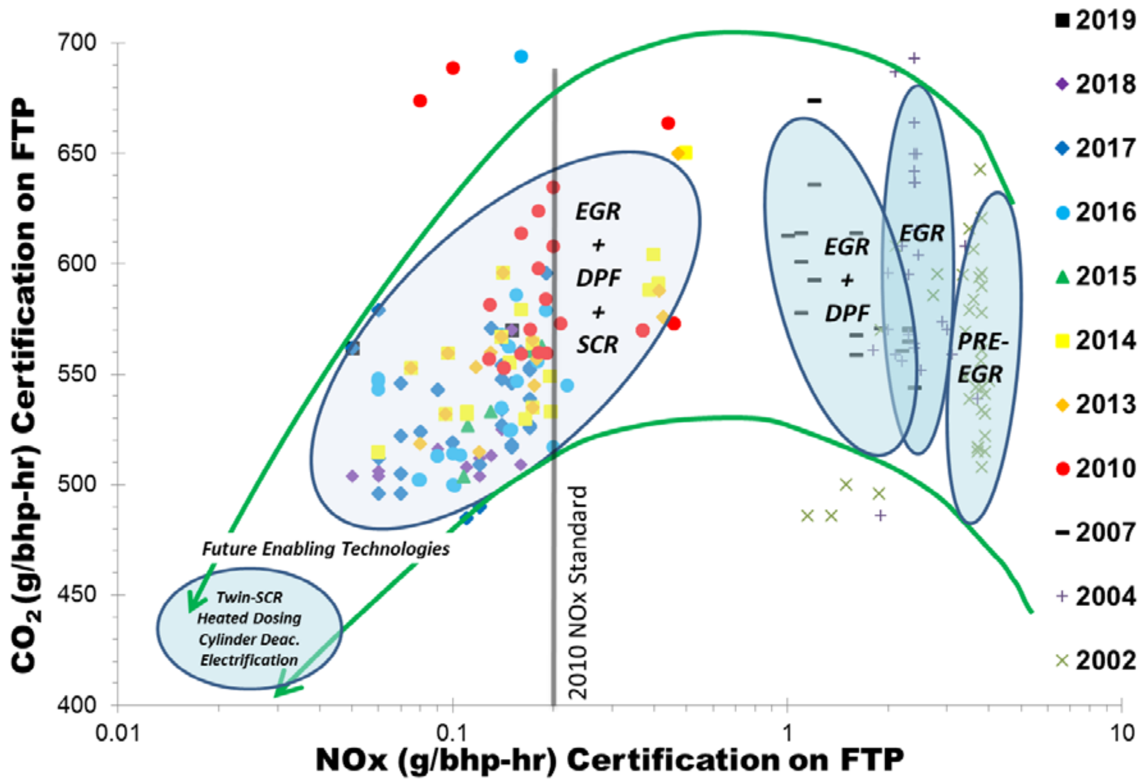


Figure 5. CO_2 and NOx certification test data for heavy-duty diesel engines certified from 2002 through 2019. Source of data: U.S. EPA (2019).

3.1 Technology Options to Meet Real World GHG and NOx Standards

One challenge with diesel engine emission control is maintaining high NOx conversion during low load operation, due to insufficient temperature in the exhaust to support efficient catalyst conversion. Diesel vehicles used in drayage activities, delivery operations, and other activities that result in high periods of idle, creep, and/or stop-and-go operation are examples of challenging duty-cycles. Traditionally, under colder operating conditions, engines would be calibrated to run hotter via higher idle speeds or fuel would be injected over the DOC to keep aftertreatment hot, both of which result in additional fuel consumption and CO_2 emissions. Recent emission control packaging architectures have included innovations in materials and designs to minimize thermal losses from the exhaust system. Double-walled exhaust pipes and canning designs with either air gaps or ceramic fiber insulation – as well as packaging exhaust components close together in a compact space, referred to as a “one box system” (see 2013 system in Figure 1) – help retain exhaust heat over longer periods of time.

In addition to physical ways to retain heat in the exhaust system, technologies can be installed on engines that deliver exhaust heat when needed. It is possible to use bypass hardware to minimize heat loss upstream of the exhaust system. Most modern diesel engines include turbochargers to provide boost and increased fuel economy and EGR systems to control NOx emissions. These can both contribute to lower exhaust temperatures by either converting the heat into useful boosting work or reducing the combustion temperature for in-cylinder NOx control which results in lower heat energy in the exhaust stream through their operation. During low speed operation and low exhaust flow, a turbocharger offers limited boost. Therefore, in the future, engines may employ turbocharger and EGR bypass valves that can be activated at times when it is more desirable to deliver hot exhaust to downstream catalysts for warm-up and stay-warm operation. Transient response challenges that may result from bypass systems can be resolved with electric assist motors built into the turbocharger or by the addition of an electric boost compressor. However, at low load a bypass alone may not yield enough heat using standard diesel engine combustion techniques. Some available thermal management strategies will provide options for engine manufacturers to calibrate engines to save fuel, which can offset the costs of the technologies.

Cylinder deactivation (CDA) is an established technology that combines hardware and computing power to shut down some of an engine's cylinders, based on the power demand, and keep the engine speed in an efficient portion of the engine map without burning more fuel or cooling the exhaust. The technology 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, trapping air and allowing the deactivated cylinder to act as a spring as the piston moves up and down the bore. Closing the valves eliminates the normal pumping losses that rob the engine of fuel efficiency and thermal energy as cold air is pumped into the exhaust. By doing this, the remaining active pistons work harder and more efficiently, thus increasing fuel economy and generating more heat to get the aftertreatment hot faster. In addition, shutting off an engine's cylinders reduces air flow through the engine and exhaust to enable heat retention in the exhaust system during low engine load operation. Both of these conditions, enabled by CDA, improve the SCR's ability to effectively reduce emissions. During low load operation, CDA has resulted in exhaust temperatures increasing by more than 100°C.

CDA has been a proven technology on light-duty vehicles for decades, but 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. Recent dynamometer testing on the FTP cycle with CDA installed on a medium-duty engine 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. 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 4-35% may be realized (using CDA below 3 bar BMEP), depending on operating mode.

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 under low load. Figure 6 shows the ability of CDA to increase exhaust temperature in diesel engine exhaust. The figure is a plot of real on-engine test data from dynamometer testing conducted at Southwest Research Institute as a part of the 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 throughout the cycle. CDA is an example of a technology that supports retaining heat in the emission controls to effectively reduce NOx while simultaneously enabling engine calibration that optimizes fuel economy.

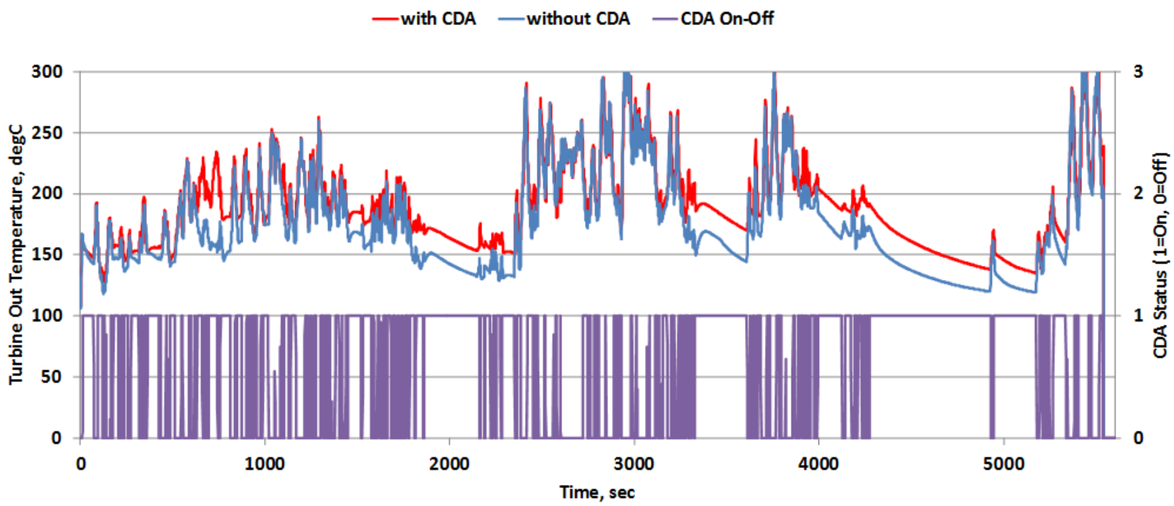


Figure 6. Exhaust temperature increase as a function of cylinder deactivation in a low load cycle.

Another promising technology category that is expected to make its way onto heavy-duty vehicles in the near future is 48-volt mild hybrid electrical systems and components. Higher voltage systems have been used successfully for years in other applications, including aviation, military, and light-duty passenger vehicles. These 48-volt systems can be found on several Mercedes, Audi and FCA vehicle models in the U.S. A primary advantage of 48-volt systems, from an implementation standpoint, is that the voltage is below the safe voltage threshold of 60 volts, which is especially important when technicians perform maintenance on the electrical system. 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. Such 48-volt technologies are being employed by most of the SuperTruck II teams. SuperTruck II is a U.S. Department of Energy initiative with a variety of goals, including the demonstration of trucks with greater than 55% brake thermal efficiency.

Mild hybridization covers a range of configurations, but a promising one includes an electric motor/generator, regenerative braking, electric boost and advanced batteries. 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. 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. The presence of a 48-volt power architecture on a truck retains the ability to power 12-volt accessories, with which drivers are familiar. 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. 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.

3.2 Achieving NOx Conversion at Low Load

NOx emission control systems have undergone a series of optimizations in order to achieve higher NOx conversion to meet future ultra-low NOx emission standards. The focus of this work has been to enable the SCR system to heat up faster after cold start, work efficiently during times of low temperature operation, and retain heat longer during times of low engine loads. To achieve a tailpipe NOx limit of 0.05 g/bhp-hr, the components used in emission control systems do not need to be redesigned and will continue to be based on a DOC, DPF and SCR architecture that exists on trucks today. The types of improvements that will likely be deployed are basic evolutionary engineering improvements such as engine calibration, better thermal management, positioning system components closer to the engine to enhance low temperature operation, better system packaging to retain heat, and the use of more active catalysts. In addition to improved aftertreatment control, there are also benefits found from earlier use of in-cylinder control measures. For example, enabling earlier introduction of EGR during the warm-up phase by utilizing an EGR cooler bypass complements the aftertreatment performance. Similarly, avoiding cooled EGR during low load conditions can increase combustion temperatures, providing benefit to aftertreatment performance. Most of these strategies have already been commercialized on light-duty diesel passenger cars and under tighter emission requirements are ready to be deployed on heavy-duty trucks.

Lessons learned from light-duty vehicles more than 15 years ago are now being applied in the heavy-duty sector. As more stringent light-duty gasoline emission standards were implemented, vehicle manufacturers began to locate catalytic converters in the close-coupled position in order to optimize cold start performance. By positioning a catalyst closer to the engine, it experiences much higher temperatures and is thus able to heat up more rapidly than catalysts placed farther downstream in the exhaust system. Currently, some light- and medium-duty diesel vehicles employ a close-coupled catalyst strategy to optimize cold-start NOx performance. Research on light-duty vehicles has shown that ultra-low levels of NOx can be achieved by utilizing an SCR on filter upstream of an SCR catalyst combined with dual dosing (Kruger, et al., 2019). Engine testing of emission controls has demonstrated that significant improvement in emissions reduction performance can be delivered by installing an additional SCR brick in front of current aftertreatment architectures in combination with dual urea dosing in heavy-duty applications (Hendrickson, Upadhyay, & Van Nieuwstadt, 2017). This design change, referred to as a light-off SCR or twin SCR, can be completed more readily than close coupling an SCR brick to the turbocharger in the engine compartment since most vehicles have available space where current aftertreatment systems are located. Much of this space exists because of the reduction in emission control volumes previously described.

A challenge with NOx emission control technologies is how to deliver the ammonia reductant at low temperatures. Traditional urea injection temperatures have been about 200°C to allow vaporization of the 70% water content of urea solution and the necessary temperature needed for hydrolysis and conversion of urea to ammonia. Catalyst evolution as shown in Figure 3 has allowed urea injection temperatures as low as 170°C. Given that it can take 10-20 minutes for the SCR to reach these temperatures in current engine and exhaust system designs, a significant amount of time may pass before the SCR reaches 50% NOx conversion, or light-off. In addition to cold start, there are low speed operating conditions where the exhaust temperature drops below 170-200°C and urea injection is stopped to prevent urea deposits from forming around the injector, mixer or on the SCR catalyst. Technology suppliers are addressing these challenges by commercializing advanced ammonia delivery techniques such as ammonia gas delivery from solid ammonia compounds or through a heated dosing strategy that converts urea solution to ammonia over a heated element or self-contained heated injector. Unlike early 2010 dosing strategies, urea delivery can now be calibrated and optimized with closed-loop control capabilities relying on feedback from NOx and NH_3 sensors. This enables accurate dosing in-use to maximize ammonia storage in the SCR and achieve high NOx conversion while minimizing overdosing of the catalyst that can result in ammonia slip and increased N_2O emissions. Section 4 of this paper provides data showing the ability of high efficiency catalyst systems to minimize N_2O formation while effectively reducing NOx emissions.

Advances in urea dosing system technology have resulted in the ability to deliver ammonia in gaseous form or to employ heated dosing of urea so that dosing can occur at lower temperatures without formation of deposits in the emission control system. Gaseous ammonia delivery systems have been around for a decade and are being commercialized on some diesel heavy-duty SCR retrofit systems. The fuel saving benefit of such a strategy is that the engine calibration can be adjusted for fuel efficient combustion rather than low engine-out NOx emissions during a wider range of engine operation beginning at lower temperatures.

Heated urea dosing systems based on multiple design principles are currently being commercialized by several manufacturers. One system design sprays urea over an electrically heated hydrolysis catalyst, resulting in rapid vaporization of the urea and conversion to ammonia for NOx reduction at lower exhaust temperatures. Another type of heated dosing design employs a heating unit built into the dosing nozzle in order to rapidly heat the urea solution as it is atomized. Heated dosing or gaseous ammonia delivery allows SCR catalysts to begin storing ammonia at temperatures down to 130°C and converting NOx at temperatures above 150°C. Heated dosing can be deployed in a full exhaust flow or partial exhaust flow design (Sharp C. , Webb, Yoon, Carter, & Henry, 2017). Figure 7 shows that dosing at lower temperatures (150°C) results in the ability to begin injecting urea up to five minutes earlier after a cold start when using a heated dosing system.

A recent study demonstrated the benefits of heated dosing achieved by spraying urea solution onto an electrically-heated catalyst (EHC) coated with a material that promotes urea hydrolysis. 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 for this catalyst. This resulted in FTP NOx emissions being reduced by 40% compared to the baseline close-coupled configuration. Furthermore, the authors demonstrated that the size of the overall exhaust system could be reduced by 50%, which could make it easier for an OEM to position the emission control system in the close-coupled position (Bruck, Presti, Holz, Geisselmann, & Scheuer, 2018). The authors of the study did not have the ability to optimize the engine calibration or urea dosing strategy for this particular engine; therefore, one might expect additional NOx reductions as suppliers partner with OEMs to fully integrate engines and aftertreatment.

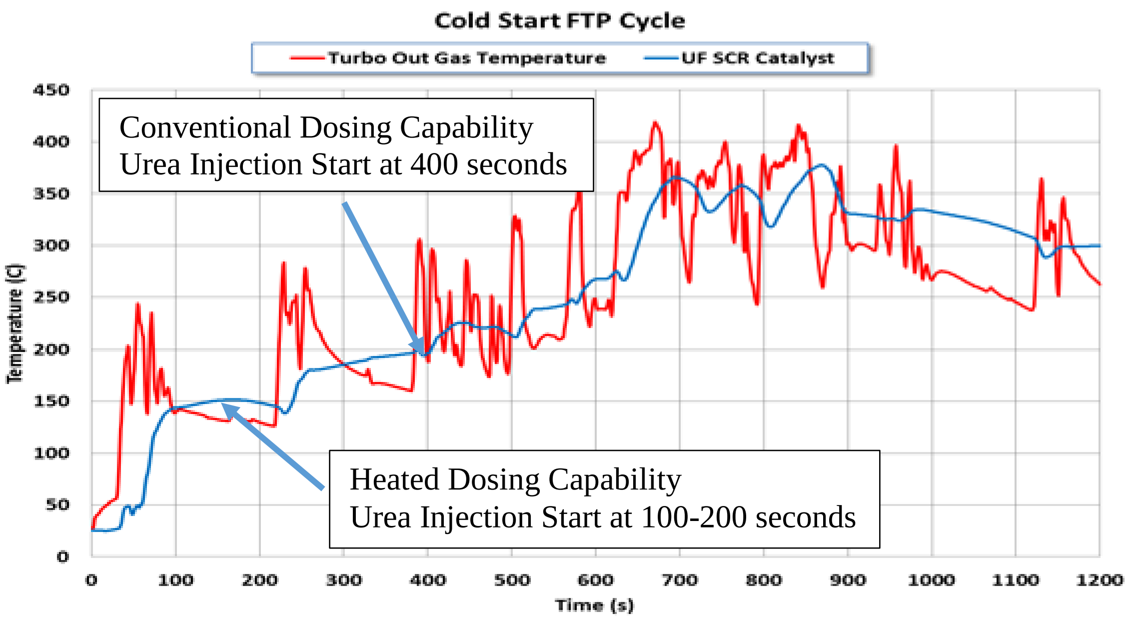


Figure 7. Effect of heated dosing on start of urea injection in SCR.

Mild hybridization, including 48V components, offers additional avenues for electrically heating the exhaust flow rapidly. For example, a 10 kW electrical heater positioned upstream of the SCR provides two benefits: directly heating exhaust and adding a 12 kW load on the engine (assuming 20% electrical losses). The latter results in secondary heat-up, totaling approximately 18 kW (assuming 50% brake thermal efficiency) in a short period of time. As previously noted, such systems are enabled by 48V starter/generators instead of larger batteries and maintain currents to levels well within the capabilities of current electrical wiring harnesses.

4.0 Feasibility Demonstration of Achieving 0.05 g/bhp-hr NOx Emissions with Current Aftertreatment Designs

Recent work conducted at Southwest Research Institute (SwRI) included a screening of several emission control architectures to evaluate the potential low NOx performance of various combinations of aftertreatment technologies and engine control strategies (CARB, 2017; Sharp C. , et al., 2017; Sharp C. , et al., 2017; Sharp C. , Webb, Yoon, Carter, & Henry, 2017). Although the objective of that work was to identify system approaches to meeting a 0.02 g/bhp-hr FTP limit, the researchers were able to meet a 0.05 g/bhp-hr limit on the composite FTP cycle by simply using better catalysts, engine calibration and heated dosing.

Since the above study used previous generation catalysts to measure the FTP emission limits on current exhaust system architectures, MECA conducted several studies using the latest catalysts and substrates being offered to engine manufacturers today for 2024 model year applications. Next generation catalysts may combine both iron and copper zeolites in a layered structure or zone-coated with two catalyst formulations on the front and rear of a single substrate. This latest work was based on dynamometer testing of a set of fully aged exhaust systems on a commercial heavy-duty engine without the benefit of a modified engine calibration. The engine testing was conducted on a MY 2014 13-liter diesel engine. The engine testing focused only on hot start FTP cycles to emphasize catalyst performance. Cold-start emission control is heavily dependent upon engine calibration, which we did not have the ability to control but an OEM would use to optimize cold start emissions performance and minimize fuel consumption. The hot start operation over the FTP can show how advanced catalysts can lead to improvements in NOx conversion, which was of primary interest in this work.

A second study used a modified engine calibration developed by SwRI as an input to an emissions model and simulated the emissions from a fully aged 2019 commercial exhaust aftertreatment system. Several scenarios were modeled, including emissions from the latest commercial catalysts and substrates over cold-start and hot-start FTP as well as low load cycles. The models also provide an evaluation of how increased catalyst and substrate volumes can affect emissions over certification cycles. Finally, the benefit of heated dosing was demonstrated over both the FTP and the low load cycle (LLC-7) developed at SwRI (CARB, 2019).

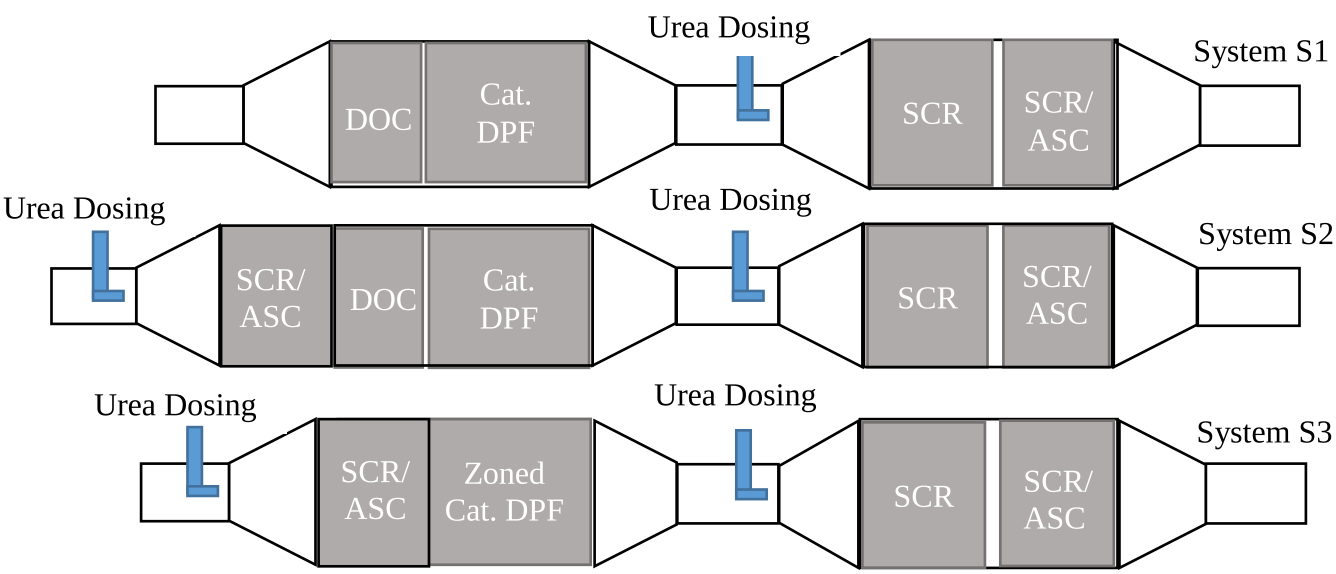


Figure 8. System configurations tested to demonstrate the feasibility of 2024 engine emissions. System S1 is based on 2019 engines in production today. System S2 employs a light-off SCR in a twin SCR arrangement. System S3 employs a light-off SCR in a twin arrangement as well as replaces the DOC and catalyzed DPF with a zoned catalyzed DPF that functions as both a DOC and DPF.

The system configurations for engine testing and modeling are shown in Figure 8 and include a traditional system layout (S1) and two advanced system layouts (S2 & S3). The system architectures displayed in Figure 8 demonstrate several options available to OEMs when designing exhaust controls for MY 2024 engines. System S1 has a similar architecture as current emission control systems but utilizes the latest generation of SCR catalysts, which are commercially available today. System S2 is a twin arrangement with light-off SCR, which adds a smaller SCR system, consisting of a second urea doser, SCR catalyst and ammonia slip catalyst, upstream of today's emission control architecture. This configuration is slightly larger than S1 but still significantly smaller than typical MY 2010 emission control systems. Finally, system S3 retains the twin SCR arrangement but combines the DOC and catalyzed DPF on to a single substrate. This zoned catalyzed DPF includes a catalyst coated on the front section of the DPF substrate that functions as a DOC and the remainder of the DPF coated with a commercial catalyzed washcoat to facilitate DPF regeneration. The zoned catalyzed DPF reduces the volume of the system to that of current system architectures and offers some reduction in thermal mass.

4.1 FTP Emission Results from Engine Dynamometer Testing

Figure 9 shows results from engine testing of the aftertreatment system configurations shown in Figure 8. In all of the engine tests, no attempt was made to modify the calibration or optimize urea dosing for the exhaust systems tested since that capability lies only with the engine manufacturers. A baseline 2014 emission control system was able to reduce hot-start FTP tailpipe NOx to less than 0.075 g/bhp-hr. Improvements in catalyst technology since 2014 have enabled trucks that employ 2019 emission control systems to meet tailpipe NOx levels over the hot-start FTP of 0.017 to 0.024 g/bhp-hr. The engine testing demonstrates that the most recent generation of SCR catalysts in a traditional emission control system architecture can yield tailpipe NOx emissions over the hot-start FTP of close to 0.02 g/bhp-hr. The addition of light-off SCR in a twin arrangement can deliver tailpipe NOx emissions below 0.02 g/bhp-hr. It should be emphasized that all of these results were achieved without the benefit of optimized engine or urea dosing calibration nor other thermal management strategies that could be employed on MY 2024 engines to further increase NOx control performance while simultaneously delivering lower CO_2 and GHG emissions.

Nitrous oxide (N_2O) emissions were measured from the three system designs. Figure 10 shows that the latest generation of SCR catalyst materials can enable tailpipe N_2O emissions close to 0.015 g/bhp-hr, which is 85% below today's Phase 2 GHG regulation cap of 0.100 g/bhp-hr. As previously stated, the total tailpipe GHG emissions footprint of a truck would be significantly reduced if N_2O emissions were trimmed. In fact, a substantial amount of CO_2 emissions could be offset if an engine were certified to the levels shown in Figure 10. For example, N_2O emissions of 0.025 g/bhp-hr would equate to a 0.075 g/bhp-hr reduction from the current cap. Given the global warming potential (GWP) of 298 for N_2O, the resulting CO_2-equivalent emissions credit would be 22 g/bhp-hr CO_2e. In this way, advanced SCR and ammonia slip catalysts are able to achieve lower N_2O emissions that manufacturers can use to trade-off for CO_2 and comply with future GHG standards.

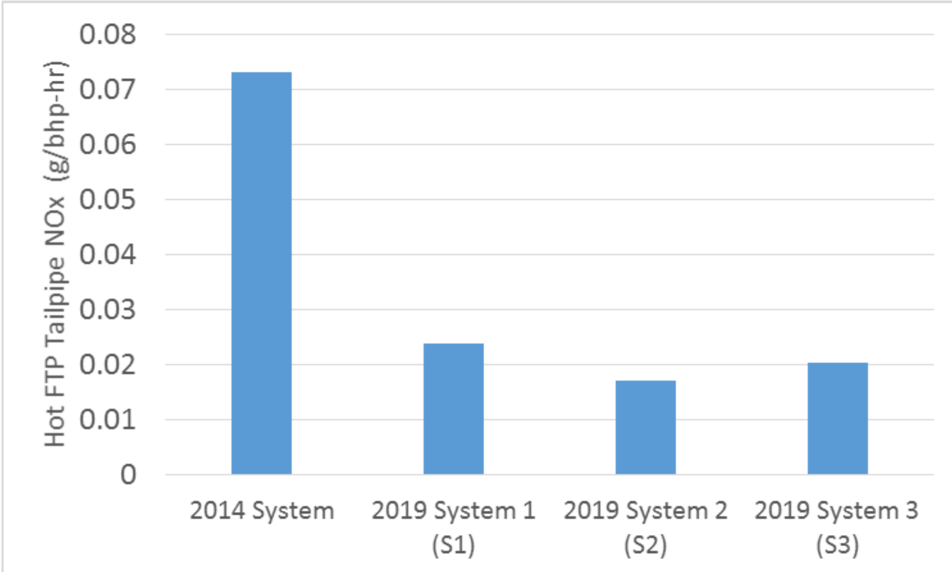


Figure 9. NOx emissions from FTP hot-start tests with four variations of emission control systems. Note: Please refer to Figure 8 and above text for description of systems.

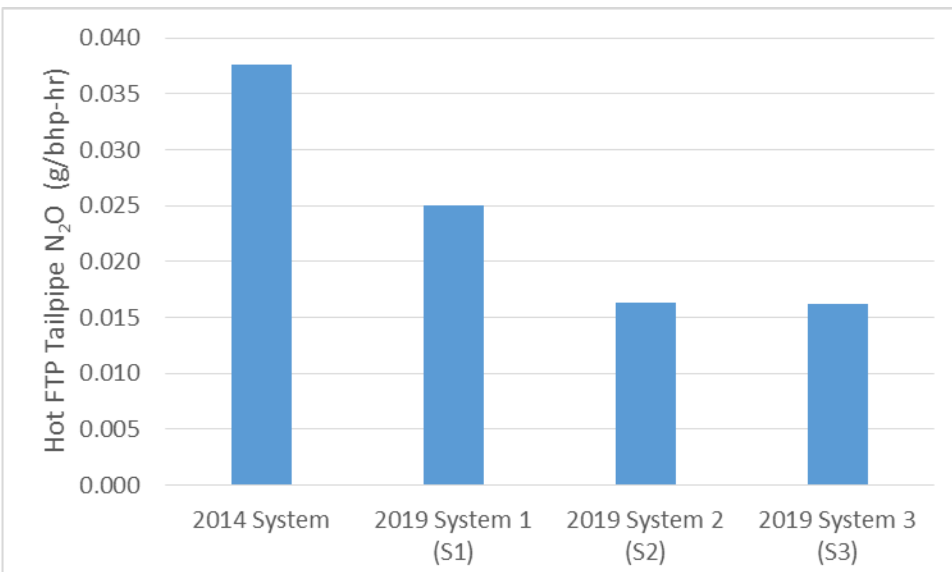


Figure 10. N_2O emissions from FTP hot-start tests with four variations of emission control systems. Note: Please refer to Figure 8 and above text for description of systems.

4.2 Modeling of Composite FTP Emissions

A model analysis was conducted using an improved engine calibration and advanced commercially available catalysts in a conventional S1 architecture from Figure 8. The emissions simulation model has been developed over ten years of commercial system testing and correlation with field parts. The model inputs include real engine out emissions from a commercial engine that was calibrated by SwRI under the CARB Low NOx Demonstration Program using an advanced cold start strategy. The catalyst conversion parameters input into the model were derived from commercially available accelerated aged catalysts under conditions that represent full useful life of 435,000 miles of operation. An industry average system SCR volume was used for the analysis. Besides in-cylinder thermal management, the model assumes no additional active thermal management, such as an additional fuel injector upstream of the DOC, and utilizes only the engine out temperature data provided by SwRI. Finally, the model assumes a single urea dosing strategy, based on the configuration shown in S1 (Figure 8), initiated at 170°C.

Figure 11 shows the predicted emissions from a commercial 2019 emission control systems with different design options. The results of the analysis indicate that currently available emission control systems at a minimum commercial SCR volume in the market today can achieve weighted composite FTP NOx emissions of less than 0.04 g/bhp-hr. The emissions over the composite FTP can be further reduced to approximately 0.03 g/bhp-hr by increasing the SCR catalyst volume to a level representing an average SCR volume found on 2019 trucks. Finally, replacing the baseline ammonia slip catalyst (ASC) with an improved, currently commercial ASC can achieve 0.02 g/bhp-hr on a composite weighted FTP cycle. This result allows for a compliance margin of 60% at an FTP NOx emission standard of 0.05 g/bhp-hr. It should be noted that the modeled hot-start FTP result was between 0.015 and 0.029 g/bhp-hr, which compares favorably with the engine test results described in the previous engine dynamometer study (Figure 9).

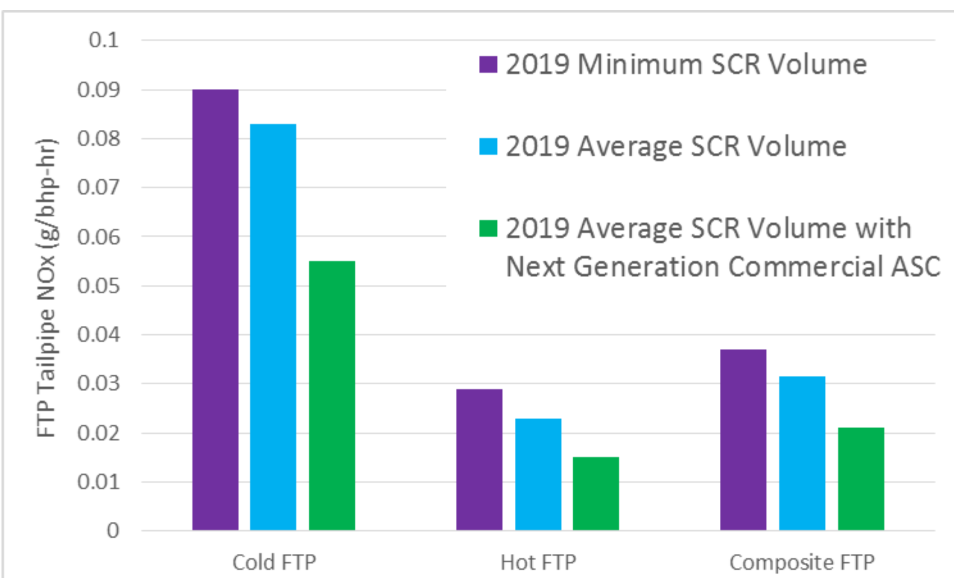


Figure 11. Modeled composite FTP NOx emissions from the latest generation commercially available SCR catalyst and two different SCR system volumes.

4.3 Modeling Emissions over the Low Load Cycle

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. Engines and exhaust emission controls can be calibrated to meet the current standard over the FTP test cycle, but a portion of real-world operation, representing low load and low speed, is challenging for engines with today's exhaust system designs and calibrations to meet current NOx standards when driving on the road. As shown above, current engines with the latest emission control technologies are able to achieve very low NOx emissions over the FTP certification cycle, as low as 0.02 g/bhp-hr NOx. Allowing for a compliance margin, we believe a standard of 0.05 g/bhp-hr in MY 2024 is achievable. However, in real world operation, these NOx emission levels may be exceeded during periods of idle or low speed operation where the SCR may cool below its catalyst light-off temperature.

MECA modeled tailpipe NOx emissions from an engine with several emission control architectures over the LLC-7 cycle developed by SwRI (CARB, 2019). The same full useful life aged catalysts were modeled at the industry-average SCR system volume as depicted by the green bars in Figure 11. The PGM loading on the DPF was varied over a range that represents the low-end to the high-end of today's commercially available DPFs to vary the NO_2 to NOx ratio delivered to the SCR. Because the low load cycle operates at an average engine load of about 7% and relatively low temperature exhaust, the modeling evaluated heated dosing as an option at a lower threshold dosing temperature range of 150°C to 170°C, compared to today's commonly used temperature of 200°C as the start of injection for SCR catalysts. As previously described in Section 3.2, heated dosing delivers ammonia at lower temperatures so the SCR can initiate NOx conversion in colder exhaust and also to overcome issues that may arise from deposit formation when using traditional dosing of urea at lower temperatures. The modeled system used a single urea doser with maximum ammonia-to-NOx ratio of 1.3. Finally, two preconditioning cycles were modeled. The first uses the FTP to precondition the SCR system to a 20% ammonia loading and the second uses a modified LLC that resulted in 50% ammonia prestorage on the SCR catalyst. The results, shown in Table 1, indicate that currently available emission controls, with the addition of heated urea dosing and 50% ammonia storage level on the SCR, can achieve tailpipe NOx emissions down to 0.18 g/bhp-hr over a low load certification cycle.

Table 1. Modeling Current Emission Controls Performance over Low Load Cycle

Model Run on Low Load Cycle	DPF PGM Loading	SCR Prestorage with NH3	Urea Dosing Temp (°C)	Tailpipe NOx (g/bhp-hr)
Baseline	X	20%	170	0.40
Scenario 1	2X	20%	170	0.38
Scenario 2	2X	50%	170	0.23
Scenario 3	2X	50%	150	0.18

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. In this report, MECA provides an assessment of cost effective technologies being commercialized by suppliers for heavy-duty on-road engines. Test results from full useful life aged systems representing commercial or market ready technology options that can be integrated on vehicles by model year 2024 were shown to exceed 0.05 g/bhp-hr on the heavy-duty FTP certification cycle and approximately 0.2 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 2024 NOx and the 2024 CO_2 standard have grown dramatically in recent years as a result of the Phase 2 GHG regulation. These strategies can be deployed on cold-start or low load operation to heat up aftertreatment and keep it hot under low engine 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 2024 to enable emission control systems to exceed an FTP NOx emission limit of 0.05 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 2024 NOx limits utilize existing aftertreatment system designs employing evolutionary improvements in technologies that have been developed over the past 17 years of experience with heavy-duty NOx regulations. Modeling shows that low temperature ammonia delivery through the use of heated urea dosing and closed loop, NOx and ammonia sensor-based control, on commercial aftertreatment systems can achieve NOx emission below 0.2 g/bhp-hr over low-load, low-speed operation.

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