STATEMENT OF THE MANUFACTURERS OF EMISSION CONTROLS ASSOCIATION ON THE U.S. ENVIRONMENTAL PROTECTION AGENCY'S ADVANCED NOTICE OF PROPOSED RULEMAKING: CONTROL OF AIR POLLUTION FROM NEW MOTOR VEHICLES: HEAVY-DUTY ENGINE STANDARDS

DOCKET ID NO. EPA-HQ-OAR-2019-0055

February 20, 2020

The Manufacturers of Emission Controls Association (MECA) is pleased to provide comments in support of the U.S. EPA's advanced notice of proposed rulemaking to revise oxides of nitrogen (NOx) emission standards for heavy-duty on-highway engines. We believe an important opportunity exists to continue to reduce NOx emissions from heavy-duty engines and vehicles due to the evolution of engine and aftertreatment technologies in the decade since the last standards were fully implemented.

MECA is a non-profit association of the world's leading manufacturers of emission control technology for mobile sources. Our members have over 45 years of experience and a proven track record in developing and manufacturing emission control and efficiency technology for a wide variety of on-road and off-road gasoline and diesel-fueled vehicles and equipment in all world markets. Now that criteria pollutants and GHG emissions are both regulated, the portfolio of products offered by our members has expanded to technologies that improve the overall emissions footprint of vehicles, including powertrain components for battery and fuel cell electric cars and trucks. In order to simultaneously meet future NOx and GHG emission standards, several pathways are available through a combination of technologies provided by MECA members. These include advanced turbochargers, EGR systems, cylinder deactivation, advanced catalysts and substrates, novel aftertreatment architectures, and dual urea dosing with optional heating. Our industry has played an important role in the emissions success story associated with light- and heavy-duty vehicles in the United States, and has continually supported efforts to develop innovative, technology advancing, emissions programs to deal with air quality problems.

MECA members represent over 70,000 of the nearly 300,000 North American jobs building the technologies that improve the fuel economy and reduce emissions of today's vehicles. These jobs are located in nearly every state in the United States – the top 10 states in the U.S. are Michigan, Texas, Illinois, Virginia, New York, Indiana, North Carolina, Ohio, Pennsylvania, and South Carolina. The mobile source emission control industry has generated hundreds of billions of dollars in U.S. economic activity since 1975 and continues to grow and add more jobs in response to environmental regulations. Emission control, engine efficiency and electric technology manufacturers invest billions of dollars each year in developing the technologies that reduce emissions from mobile sources.

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, the United States Environmental Protection Agency (EPA) should revise the heavy-duty truck emission standards, with a particular focus on tighter limits for oxides of nitrogen (NOx) and particulate matter (PM). MECA published two white papers (attached to these comments as Appendix 1 and Appendix 2) that provide detailed information on technology feasibility and cost-effectiveness. The first paper focuses on achieving a 0.05 g/bhp-hr limit beginning with model year (MY) 2024 engines through the use of current system architectures and the latest generation of commercial catalysts hardware (MECA, 2019). The second paper focuses on achieving a 0.02 g/bhp-hr limit on the current certification cycles and the ability to meet a future limit on a new test cycle that represents low load operation beginning with MY 2027 engines (MECA, 2020). The results of MECA's analyses conclude that:

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.

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.

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.

4. 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.

5. The estimated cost of future emission controls hardware 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.

MECA SUPPORTS ASSESSMENT OF BOTH COSTS AND BENEFITS IN THE GUIDING PRINCIPLES FOR THIS RULEMAKING

EPA requested comment on the principles that have guided previous rulemakings and shall guide the agency for the CTI. These include the goal to reduce in-use emissions under a broad range of operating conditions; consider and enable effective technological solutions while carefully considering the cost impacts; compliance and enforcement provisions should be fair and effective; regulations should incentivize early compliance and innovation; ensure a coordinated 50-state program; actively engage with interested stakeholders. These guiding principles are missing an analysis of the air quality, health and welfare benefits that must be balanced against the costs. Without a proper assessment of the benefits, it is not possible to determine if the costs are justified. For example, an analysis that only considers costs may improperly determine a regulatory outcome is not warranted due to the appearance of a high-cost value. However, a full assessment that includes calculation of the benefits may demonstrate that costs are outweighed by benefits and thus provide validation of the rule.

MECA BELIEVES THAT AN IMPLEMENTATION DATE BEGINNING WITH MY 2027 PROVIDES SUFFICIENT LEAD TIME FOR SUPPLIERS TO WORK WITH THEIR CUSTOMERS TO MEET FUTURE STANDARDS

EPA requested comment on the goals that the program: not undermine the industry's plans to meet the CO_2 and fuel consumption requirements of the Heavy-duty Phase 2 program and not adversely impact safety; leverage ‘‘smart’’ communications and computing technology; provide sufficient lead time and stability for manufacturers to meet new requirements; streamline and modernize regulatory requirements; support improved vehicle reliability. In the comments that follow as well as the two white papers recently published by MECA (MECA, 2019; MECA, 2020), we demonstrate that multiple technology pathways are available and implementable before MY 2027. MECA also supports streamlining and modernizing regulatory requirements such that the benefits of current and emerging technologies can be demonstrated during certification. For example, MECA supports taking lessons learned from EPA's upcoming changes to Heavy-duty Phase 2 technical amendments to allow novel testing to certify hybrid electric vehicles and apply these to criteria emission certification procedures for engines to be incorporated into electrified vehicles.

MECA SUPPORTS THE PRIORITIZATION OF LOW-NOx TRUCKS IN PROGRAMS TO REDUCE EMISSIONS FROM THE EXISTING FLEET.

EPA requested comment on the extent to which the technologies and solutions could be used by state, local, or tribal governments in reducing emissions from the existing, pre-CTI heavy-duty fleet. MECA suggests prioritizing projects that propose to repower or replace in-use vehicles with ultra-low NOx engines for funding by EPA's Clean Diesel Program. As currently proposed, CARB is likely to set a NOx standard of 0.05 g/bhp-hr beginning with MY 2024 and from 0.015 to 0.030 g/bhp-hr beginning with MY 2027, and several Section 177 states are likely to adopt these standards. A signal from EPA's Clean Diesel Program that these lower-emitting NOx trucks will be prioritized in grant funding requests would incentivize OEMs to provide more of these trucks for sale.

FURTHER NOx REDUCTIONS ARE NECESSARY

Inventory modeling

Hundreds of millions of people in the U.S. still breathe unhealthy air. Large populations of citizens in the U.S. live in regions that are in ozone nonattainment that would benefit from a lower NOx limit on heavy-duty engines. In a 2017 meeting of the Mobile Source Technical Review Subcommittee, EPA presented inventory projections showing large contributions of heavy-duty vehicle NOx emissions to ambient ozone and secondary $PM_{2.5}$ levels in 2025 (U.S. EPA, 2017).

MECA recently funded an emission inventory analysis of the CTI, covering the modeling domain of the contiguous 48 U.S. states and the District of Columbia for the calendar year 2035. The foundation of the evaluation was the current EPA inventory projection for 2028. The 2028 inventory projection is that of the 2016v1 emissions modeling platform. It is a product from the agency's National Emissions Inventory Collaborative and includes a full suite of the base year (2016) and the projection year (2023 & 2028). This part of the analysis is referred to as the "2028 Base Case" inventory in this study and corresponds closely with a 2027 implementation date for the CTI rule. From that inventory foundation, two new inventory scenarios were developed as follows.

- The "2035 Base Case" inventory was developed to include an on-road fleet projection to 2035 with no change in the underlying regulatory context.
- The "2035 Control Case" inventory was developed to include both the 2035 fleet projection and the impacts of adoption of federal FTP standards for heavy-duty trucks of 0.05 g/bhp-hr beginning with MY 2024 and 0.02 g/bhp-hr beginning with MY 2027, as proposed by CARB, on on-road vehicle emissions.

The 2035 on-road fleet projection estimated hours, VMT and vehicle populations at the county, roadway type, fuel type and vehicle class level. The resources used to create the fleet projection were EPA's 2023 and 2028 activity projections (used to capture trends at the desired resolution by county, roadway type, fuel type and vehicle class level) and the current version of the Energy Information Administration (EIA) *Annual Energy Outlook 2019* (used for national-level vehicle and VMT projections on which the trends were renormalized to match the national growth rate estimated by the EIA). The fleet-turnover impacts included in the 2035 inventories – both with and without the impacts of the CTI – were modeled with EPA's MOVES2014b model (MOVES2014b-20181203, which includes the December 2018 technical update). Fleet-turnover effects were modeled relative to the 2028 Base Case with MOVES at the national scale. Inputs into this modeling included EPA's 2028 age distribution data aggregated to the national level – assumed unchanged for 2035 – and emission factor updates to include the impacts of the CTI.

Preliminary results from the inventory analysis (to be published later this year) show that the new modeled FTP limits would result in a nationwide reduction of 330,000 tons per year of NOx in 2035. On a state-by-state level, the NOx inventory reductions from the heavy-duty fleet are about 60-70% below the 2028 base case (Figure 1). When taking a more refined look at the location of the NOx benefits at the county level, those counties currently in nonattainment or maintenance with the 2015 ozone NAAQS will receive some of the highest NOx reductions (e.g.

> 145 tons NOx in 2035) from a 0.02 g/bhp-hr heavy-duty engine FTP standard (Figure 2). These estimates likely represent best-case, conservative values of real-world NOx reductions because the current version of MOVES does not have the latest emission factors representing low-load and low-speed truck operation. The agency is updating the next version of MOVES to represent emissions in these challenging duty-cycles more accurately. This update is expected to bring real world NOx emissions down further once the emission factors of future certification that includes a low-load cycle are factored into the model. In addition to the modeled NOx reductions, our preliminary analysis suggests reductions of 2,300 tons of VOCs and 83,000 tons of carbon monoxide in 2035. Both NOx and VOC contribute to ozone formation.

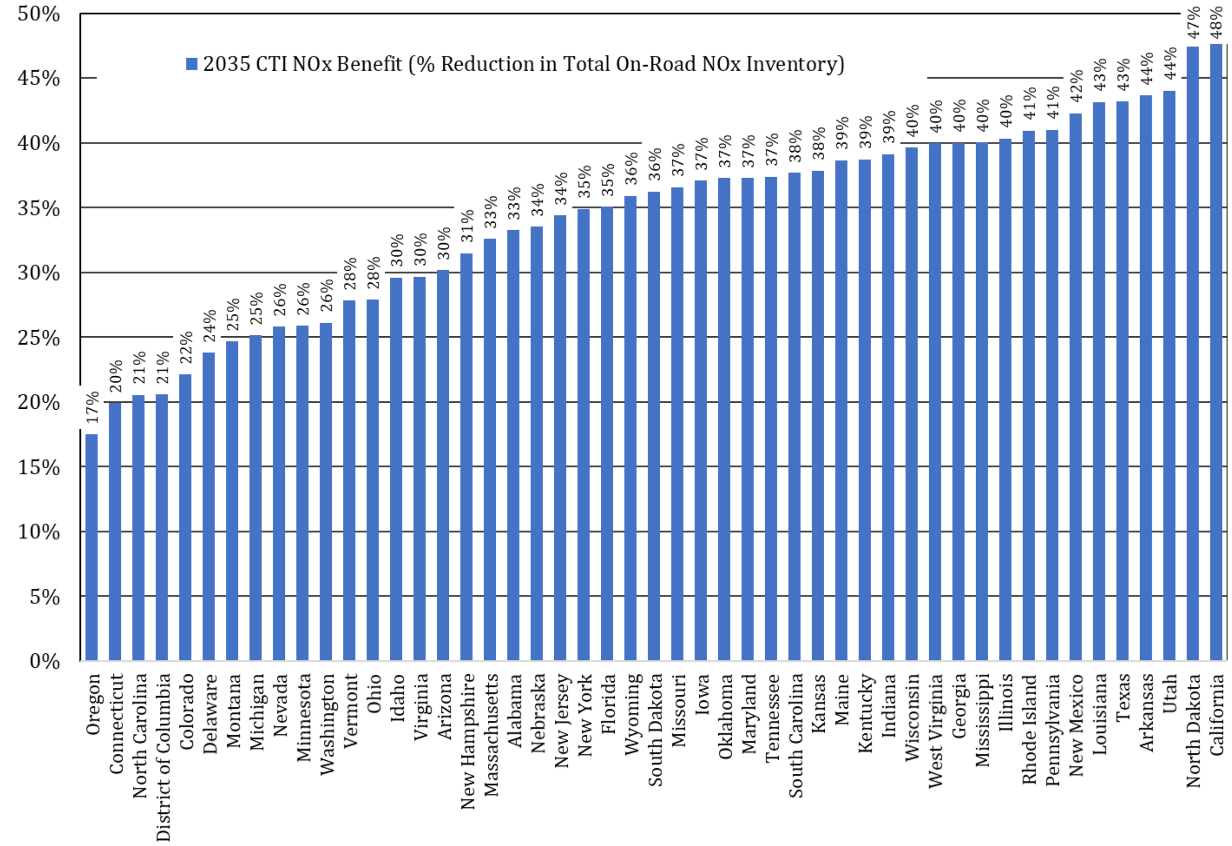

Figure 1. CTI NOx Annual Benefit in 2035 as a Percent Reduction in Total On-Road Inventory

Environmental justice communities

Communities near freeways, ports and freight corridors experience acute environmental impacts, including air pollution and noise, due to high heavy-duty truck traffic. Many studies have shown health risks related to living in areas with air quality affected by goods movement emissions. Many of these communities include high populations of mostly low-income and minority citizens, which raises environmental justice concerns. What is interesting about Figure 2 is that some of the highest county-level NOx reductions from a national CTI program are found in major metropolitan regions and along highways involved in goods movement and populated by EJ communities as highlighted in the map, outlining major freight arteries.

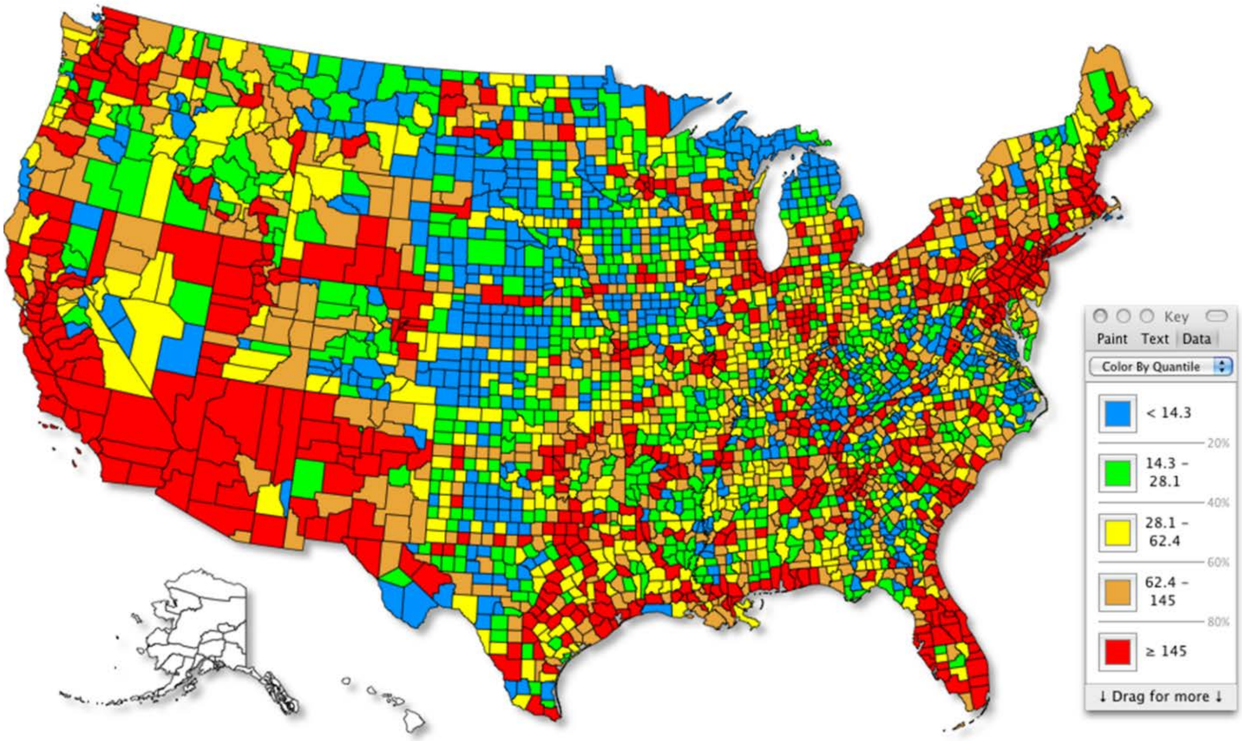

Figure 2. Modeled NOx Reductions by County from Cleaner Trucks Initiative in 2035 (tons).

MECA estimated that these reductions could 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, replacing 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 $2,000-$21,000 per ton (U.S. EPA, 2017). Similarly, CARB estimated the cost-effectiveness for future low-NOx requirements to be approximately $6,000 per ton (CARB, 2019).

MECA SUPPORTS ALIGNED NOx STRINGENCY AND FINAL IMPLEMENTATION DATES WITH CALIFORNIA AIR RESOURCES BOARD

Federal standards provide certainty

Technology commercialization has a long cycle, including testing, design and real-world deployment across many trucks in the field to make sure systems are reliable and durable. This cycle is why stringent standards are a critical signal to industry to make investments today for technologies that will be needed in the future. MECA members are engaged in developing a large portfolio of technology options that can be installed on a vehicle to optimize the lowest NOx and CO_2 emissions. MECA supports federal standards founded on technologically feasible and cost-effective solutions that allow communities to meet their air quality goals. Several years ago, CARB initiated its rulemaking process on the next set of heavy-duty engine standards, including feasibility demonstrations and technical working group discussions. Much of this documentation is available for EPA to reference and incorporate into its rulemaking analysis. Because of the time spent by CARB to date and the likelihood that California finalizes its heavy-duty engine regulation before EPA's final rule is completed, we support EPA harmonizing with CARB's provisions as adopted by their Board. Harmonization with CARB's regulatory provisions would provide certainty to suppliers, which have made investments in research and development to prepare for the future needs of their customers. MECA supports a federal implementation date beginning with MY 2027 because this harmonizes with CARB's second step of NOx standards as well as the final step in the Heavy-Duty GHG Phase 2 standards. Aligning criteria and GHG standard implementation dates enables optimization of NOx and CO_2 emissions simultaneously. This alignment is the most cost-effective approach for engine manufacturers as many technologies described below offer simultaneous and synergistic reductions in both NOx and CO_2.

Technologies are now commercially available, and can be integrated into trucks to meet a 0.02 g/bhp-hr FTP NOx standard by 2027

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 (MECA, 2020). Ongoing work by MECA members and SwRI 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 several thermal management and heating strategies to reduce engine-out NOx emissions and achieve real-world NOx reductions during the most challenging low speed and low load operating conditions. New aftertreatment architectures, that employ a close-coupled selective catalytic reduction (SCR) catalyst before the diesel oxidation catalyst (DOC) and diesel particulate filter (DPF) in a twin SCR system arrangement with dual urea dosing, can meet future FTP/RMC NOx limits of 0.05 g/bhp-hr by 2024 and a final limit between 0.015-0.03 g/bhp-hr in 2027 that California is proposing to phase in. 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 validated on fully aged catalysts and engine testing on dynamometers have demonstrated the ability to achieve NOx levels as low as 0.015 g/bhp-hrs over the FTP and below 0.075 on the proposed LLC certification cycles using preliminary calibration from SwRI (MECA, 2020). Over the next five years, suppliers will continue to optimize their components and engine manufacturers will hone their calibrations to exceed what has been demonstrated to date. This continued improvement work is why MECA believes that a limit of 0.02 g/bhp-hr is a technically achievable final standard for a national program by 2027.

The 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 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 many 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 SCR NOx reduction performance (Sharp, CARB Low NOX Development and Demonstration Programs at SwRI Progress Update, 2019).

Engines can be designed and optimized for simultaneous reductions in NOx and CO_2 emissions

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 DPFs 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 thermodynamics. 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 EGR from the engine and SCR in the exhaust, and every generation of SCR system 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 in 2010-2011, the inverse relationship between CO_2 and NOx emissions at the tailpipe was overcome and both were reduced simultaneously (see Figure 3 below). 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. By setting stringent emission targets for both CO_2 and NOx through realistic regulations, calibrators have expanded their toolbox from the engine to the powertrain to enable simultaneous NOx reductions and engine efficiency improvements.

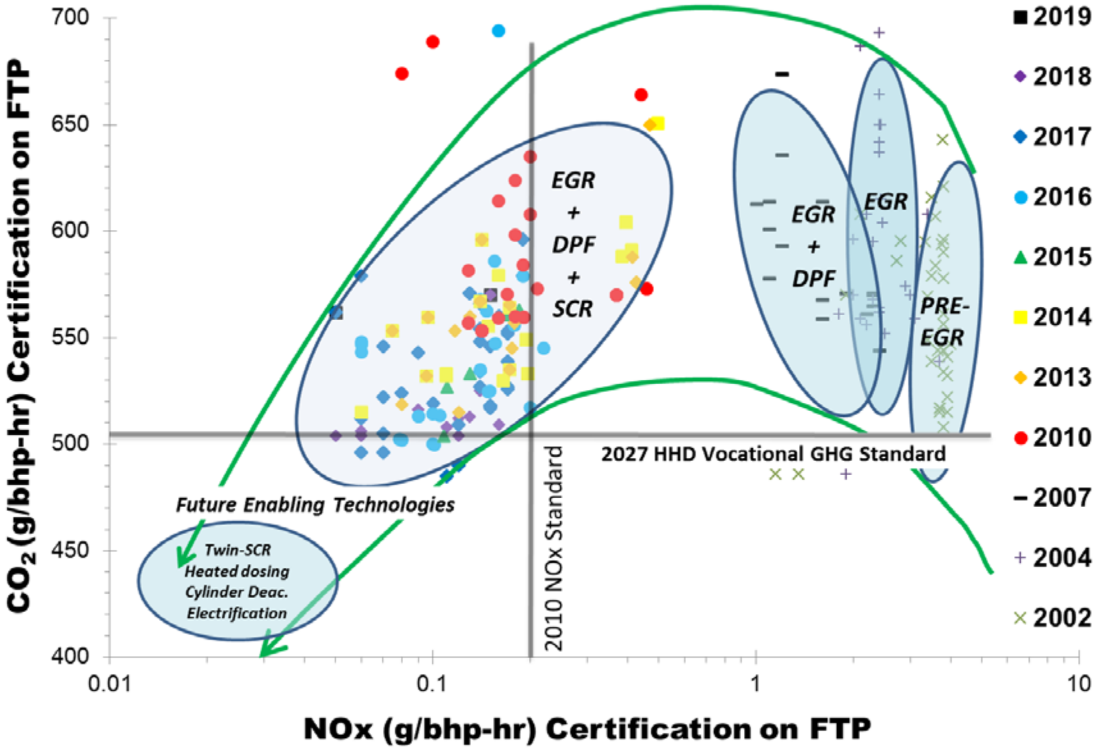

Figure 3. Heavy-Duty Engine Certification Test Data for NOx and CO_2.

EFFICIENCY AND EMISSION CONTROL TECHNOLOGIES CAN ENABLE ENGINES TO MEET STRINGENT NOx LIMITS WHILE IMPROVING FUEL ECONOMY AND REDUCING CO_2 EMISSIONS

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 in the SCR. Diesel vehicles used in drayage, 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" – help retain exhaust heat over long periods.

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 in turbochargers or EGR coolers, 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 or mechanically driven boost compressor. However, at low load a bypass alone may not yield enough heat using standard diesel engine combustion techniques. Several thermal management strategies will provide options for engine manufacturers to calibrate engines to save fuel, which can offset the costs of the technologies to their customers.

Cylinder deactivation and Variable Valve Actuation

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. Based on decades of experience with CDA on passenger cars and trucks, CDA 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 programming is particularly important for vehicles that spend a lot of time in creep and idle operation modes. 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 (MECA, 2020).

The use of variable valve actuation (VVA) is another approach for active thermal management. VVA approaches include: early exhaust valve opening (EEVO), early intake valve closing (EIVC) or late intake valve closing (LIVC), all considered active thermal management strategies. Both EIVC and LIVC reduce the amount of air trapped at valve closing. Both methods reduce the effective compression ratio and volumetric efficiency, resulting in lower NOx emissions and reduced air-fuel ratio, and in turn, hotter exhaust temperature. EEVO results in hotter exhaust gas to heat-up aftertreatment; however, more fueling is needed to maintain brake power output. This results in a CO_2 emissions penalty that must be accounted for in calibrating for better fuel economy and higher engine-out NOx during hot operation when the SCR can be used to remediate NOx emissions. VVA offers some potential cost savings and is therefore used in some medium-duty applications as a fast heat-up strategy. OEMs will have multiple pathways at varying costs to achieve their thermal management objectives and achieve ultra-low NOx emissions in low-load and low-speed operation.

Advanced turbocharger technologies

Modern turbochargers

Modern turbochargers have a variety of available design 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.) advanced 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. The latest high-efficiency turbochargers are one of the more effective tools demonstrated in 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 efficient. This improvement allows for very low particulate generation and even low engine-out NOx.

Turbocompounding

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 estimated 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, et al., 2017-01-0958, 2017; Sharp, et al., 2017-01-0954, 2017; Sharp, Webb, Yoon, Carter, & Henry, 2017). While turbocompounding has the potential to reduce fuel consumption, it can result in lower exhaust temperatures that can challenge aftertreatment performance. Therefore, it is 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.

Driven turbochargers

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. 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. 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, including the ability to decouple EGR from boost pressure, reduce transient engine-out NOx, and improve aftertreatment temperatures during cold start and low load operation. Bypassing a driven turbine can provide quick temperature rises for the aftertreatment while still delivering 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 (MECA, 2020).

Electrification: Mild Hybridization

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 Europe) from Mercedes, Audi, VW, Renault 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 trademark. 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.

Similar to the passenger car fleet, truck OEMs are considering replacing traditionally mechanically-driven components with electric versions 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. 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. 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. By shutting off the engine at idle or motoring using start/stop, micro hybrid technology can help to maintain aftertreatment temperature by avoiding the pumping of cold air through the exhaust. Capturing braking energy and storing it in a small battery for running auxiliary components when the engine is off offers another CO_2 reducing strategy for OEMs to deploy.

In lighter medium-duty applications, 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 (MECA, 2020).

Electrification: Full hybridization and electric vehicles

Full hybrid configurations are currently found on several models of light-duty passenger cars and light trucks in the U.S. and a limited number of medium-duty trucks. 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 larger electric motors and batteries, which support greater acceleration capability and regenerative braking power. 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 without returning to a central location. Full hybrid vehicles have made the highest penetration into parcel delivery, beverage delivery and food distribution vehicles because they can take advantage of regenerative braking in urban driving (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, 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 is 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 (MECA, 2020).

EPA requested comment on the likely market trajectory for advanced powertrains as well as any barriers or incentives that EPA could consider to better encourage emission reductions from these advanced powertrain technologies. As noted above, the types of technologies that enable electrified heavy-duty vehicles are already commercially available with more anticipated by 2027. Some barriers that remain, such as infrastructure needs, are outside the scope of this regulation. MECA supports the inclusion of revised certification procedures in the CTI that allow for a better demonstration of the criteria pollutant benefits offered by certain powertrain technologies. Current engine certification procedures for criteria pollutants do not accurately account for the benefits of electrified technologies, including hybrid electric vehicles and stop-start systems. MECA supports alternative test methods, such as those being considered in the Heavy-duty Phase 2 GHG technical amendments, to be available for certification of engines and vehicle systems to criteria emission standards. For example, MECA supports powertrain testing, powertrain-in-the-loop, and engine-in-the-loop test methods.

MECA also supports the option for technology suppliers to provide criteria pollutant data directly to EPA that could be used to verify the emission benefits of specific technologies. These technologies could then be included in a list or drop-down menu of NOx emission credits for OEMs to use to calculate emission limit values when certifying engines that include technologies from the menu. Finally, MECA supports the ability of OEMs to generate NOx emission credits when over-complying with the standards set by CTI, and these credits could be used in an averaging, banking, and trading system similar to other regulations in place today. MECA supports technology-neutral standards and therefore does not support credits that are technology-specific or favor one technology over another.

OPTIMIZATION OF AFTERTREATMENT TECHNOLOGIES CAN REDUCE NOx EMISSIONS FROM ENGINES BY OVER 90%

Evolution of aftertreatment systems

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. In 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. Manufacturers continue to improve SCR substrates to increase geometric surface area, allow uniform catalyst coating, reduce back pressure on the engine, and reduce thermal mass. As OEMs gained experience with engine calibration, catalyst suppliers made improvements to the performance of aftertreatment systems 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 evolutions that have enabled system downsizing to occur over the past ten years include new substrates with thinner walls and higher porosity, which result in 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 further 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 (MECA, 2019).

Selective catalytic reduction (SCR)

SCR catalysts and substrates

Catalyst manufacturers have continually improved SCR performance by focusing on low and high temperature activity to broaden the overall temperature window of operation. Higher activity catalysts have resulted in system downsizing and, ultimately, cost savings for their customers. An alternate approach to downsizing may be to increase the catalyst loading at the same pressure drop and reduce NOx emissions. Low-temperature NOx conversion by the latest advanced catalyst systems can be further improved with increased catalyst loading. 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.

Advanced urea dosing strategies

The catalytic reduction of NOx over SCR catalysts requires the use of a reductant such as ammonia, which can be delivered as gas or atomized aqueous urea solution (known as diesel exhaust fluid or DEF) that is converted to ammonia in the 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. Light-duty vehicle OEMs have recently introduced dual (or twin) urea dosing systems, which are used in conjunction with a twin SCR catalyst design (described more below). This type of architecture is a cost effective and technologically feasible solution to achieve a significant reduction in NOx.

Advanced ammonia slip catalysts

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. These methods have allowed SCR and ASC catalysts to be zone coated on one substrate, which reduces system size and thermal losses.

Electrically-heated catalysts (EHC)

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, 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 for thermal management in the light-duty vehicle sector. As discussed in MECA's 2024 technology white paper, heated dosing can be achieved by spraying urea solution onto an 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.

Twin SCR architectures

Lessons learned from light-duty vehicles more than 15 years ago can be 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 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 underfloor location. Currently, some light- and medium-duty diesel vehicles employ a close-coupled catalyst strategy to optimize cold-start NOx performance. 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. This design change, referred to as a light-off SCR or twin SCR, can be implemented more readily than close coupling an SCR brick to the turbocharger in the engine compartment since most vehicles have limited space in the engine compartment. The introduction of real driving emissions (RDE) certification requirements in Europe has led to the introduction of twin SCR configurations with dual urea dosing on some light-duty vehicles in Europe. Suppliers have expertise with such designs that they can introduce into the heavy-duty sector.

Passive NOx Adsorber (PNA)

One technology that has evolved specifically to address cold-start NOx emitted at low exhaust temperatures beginning at room temperature, includes a family of new materials referred to as passive NOx adsorbers (PNA). This catalyst technology is used upstream of the traditional exhaust control system, in combination with the DOC, to trap and store NOx at temperatures between room temperature and 200^{o}C before urea can be dosed into the hot exhaust. Once the exhaust temperature is sufficient for SCR catalysts to convert NOx to nitrogen, and to allow the urea dosing system to be activated, the NOx stored on the PNA begins to desorb so it can be converted by the ammonia reductant over the downstream SCR catalyst. This emerging technology was demonstrated in the Stage 1 CARB low NOx demonstration program and has been discussed in several SAE technical papers (Sharp, et al., 2017-01-0958, 2017; Sharp, et al., 2017-01-0954, 2017; Sharp, Webb, Yoon, Carter, & Henry, 2017). PNA technology may be one of the strategies available to engine and vehicle manufacturers to achieve lower cold-start tailpipe NOx levels.

Closed crankcases

MECA members offer closed crankcase filter systems into medium- and heavy-duty applications as a cost-effective way to control PM emissions. On engines that have open crankcase ventilation, as tailpipe PM has been reduced through the use of DPF technology starting in 2007, crankcase PM became a more significant fraction of the overall PM footprint of the vehicle. Because the DPF is over 95% effective at reducing tailpipe PM, measurements have shown that crankcase PM can represent over 60% of the total PM footprint of a 2007 DPF equipped truck. MECA supports controlling these PM emissions from all diesel engines.

Crankcase PM can have similar toxicity as tailpipe PM because it contains known carcinogens such as PAH and heavy-metals found in used engine oil. Crankcase PM can be emitted as an aerosol in the micron particle size range, allowing it to be inhaled. Accumulated droplets can also be deposited on the ground and impact water quality.

Costs to achieve future standards

MECA estimated the costs (in 2019$) of the hardware being tested at SwRI in the CARB low-NOx demonstration program (MECA, 2020). This includes CDA on the engine and a twin SCR aftertreatment architecture. The cost results were compiled by an independent third party to represent a range of costs for a full emission control (on engine plus 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. A complete cost analysis conducted by NREL 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. 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 cost 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, Costs of Emission Reduction Technologies for Heavy-Duty Diesel Vehicles, 2016).

For a Class 8 line-haul tractor with a 12-13L engine, we estimate the cost of the engine and aftertreatment hardware to be in the range of $3,500 to $4,600 per truck. This cost is about 10%-30% less than that estimated by the 2016 ICCT 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. The 2016 ICCT study also reported that the average price of a heavy-duty line-haul truck has historically increased by about 1% per year 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 continually reduce the costs of their components through manufacturing improvements and other optimization. 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 increasing price of a heavy-duty truck, 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 a CDA-enabled engine and twin SCR emission control system. To meet these tighter standards, the technology evolution (discussed above and in MECA's 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 (MECA, 2019). 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 at its 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.

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 CARB January 23, 2019 workshop) 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. 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.

MECA SUPPORTS MORE STRINGENT HEAVY-DUTY GASOLINE STANDARDS

Gasoline engine exhaust emission control

MECA supports EPA's historical approach of setting fuel neutral standards for vehicles and engines. Furthermore, we believe that technology available for reducing exhaust emissions from light-duty vehicles and medium-duty chassis certified vehicles has advanced significantly and can be applied to engine certified products. The technology base of advanced three-way catalysts deposited on high cell density, thin-walled substrates has evolved dramatically from light- and medium-duty chassis certified vehicles to comply with Tier 3 and LEV 3 standards. Catalyst manufacturers have developed coating techniques based on layered or zoned architectures to strategically deposit precious metals in ways that optimizes their performance at a minimum of cost. The coated substrates are then packaged using specially designed matting materials and passive thermal management strategies, secondary air injection systems to allow light-duty trucks to meet the stringent Tier 3 emission fleet average limit of 30 mg/mile or approximately 100 mg/bhp-hr. Close-coupled catalyst exhaust architectures have been on light-duty vehicles starting with Tier 2 standards and are an effective strategy for addressing cold-start or low load operation. These same approaches can be readily optimized and applied to allow all medium-duty, and heavy-duty gasoline vehicles to achieve the same ultra-low exhaust emission levels being considered for diesel engines by this rule.

In 2007, MECA applied the above-mentioned strategies to two full-sized 2004 pick-up trucks equipped with a 5.4L and 6.0L engine (Anthony & Kubsh, 2007). The aftertreatment systems were packaged with dual-wall insulated exhaust systems and fully aged to represent 120,000 miles of real-world operation. Even without engine calibration optimization, both vehicles achieved FTP NMHC+NOx emissions of 60-70 mg/mile. Although we did not replace the cast-iron exhaust manifolds on these vehicles, an OEM likely would take advantage of such passive thermal management strategies, including dual wall insulated exhaust, to further reduce cold-start emissions.

Engines and aftertreatment systems have evolved significantly over the past 15 years and in fact, in support of the Tier 3 light-duty regulation (U.S. EPA, 2013), EPA tested a 2011 LDT4 pick-up truck with a 5.3L V8 engine and MECA supplied 150K mile aged aftertreatment system consisting of advanced catalyst coating on 900 cpsi substrates in the close-coupled location as well as underfloor catalysts. The system achieved an FTP NMHC+NOx level of 18 mg/mile. We believe that these same technology approaches can be deployed on medium-duty gasoline engines to meet the same stringent emission levels being considered for medium-duty diesel engines.

Tighter PM Standards for HD Gasoline Engines

MECA agrees with EPA that there is an opportunity to further reduce PM emissions from HD gasoline engines in the spirit of having fuel neutral standards for this sector. CARB is proposing to tighten PM by 50% to 0.005 g/bhp-hr for diesel engines and MECA believes that would not require any change in technology but only serve as a backstop to prevent backsliding under a tighter NOx limit. As fuel efficiency standards tighten and GDI injection technology becomes more common on commercial vehicle engines, the PM emissions from medium and heavy-duty gasoline engines are likely to increase dramatically. The European Commission, China and India have adopted a particle number emission standard for light-duty vehicles powered by gasoline direct injection (GDI) engines as a part of their Version 6 light-duty emission standards. Europe implemented the PN limit for all vehicles in 2019, and China and India will implement it in 2020 and 2023, respectively. China will require all vehicles to meet this limit in 2023, including gasoline port fuel injected vehicles. This PN standard established a more stringent particle emission limit for GDI vehicles in the same time frame as EPA's 3 mg/mile PM standard that will complete phase-in with the 2021 model year. The Euro 6 GDI particle number limit has been set at $6 \text{ X } 10^{11}$ particles/km, measured using the European PMP particle measurement protocol and is approximately equivalent to 0.5 mg/mile. This European particle number limit will cause auto manufacturers to introduce cleaner technologies such as advanced fuel injection systems and/or gasoline particulate filters. Nearly all auto manufacturers that sell into the European or Chinese markets are using particulate filters on gasoline direct injection vehicles, including some PFI vehicles.

MECA funded a test program at SwRI as part of the stage 1 Low NOx demonstration to characterize the PM and PN emissions from a CNG engine emitting 0.01 g/bhp-hr NOx (Khalek, Badshah, Premnath, & Brezny, 2018). Although this CNG engine emitted very low PM mass levels, the PN emissions were an order of magnitude greater than a low NOx diesel engine with a DPF. A GPF or DPF wall-flow filter provides the co-benefit of also reducing toxics and carcinogens like PAH that are associated with GDI and PFI PM by over 90% (Yang, et al., 2018).

Gasoline engine evaporative emission control

In the ANPR, EPA requests comment on technologies to address evaporative emissions for heavy-duty gasoline vehicles (HDGVs). Specifically, EPA requests comment on (1) expanding Onboard Refueling Vapor Recovery (ORVR) to incomplete HDGVs rated over 14,000 lbs. Gross Vehicle Weight Rating (GVWR); (2) challenges of multiple manufacturers to appropriately implement ORVR systems on the range of heavy-gasoline-fueled vehicle (HDGV) products in the market today; and (3) refueling test procedures, including appropriateness of engineering analysis to adapt existing test procedures that were developed for complete vehicles to apply for incomplete vehicles.

The US EPA and CARB regulatory framework offers the most comprehensive evaporative control program in the world for chassis certified vehicles. On-Board Refueling and Vapor Recovery (ORVR) has been successfully implemented in the US and Canada for over 25 years. There have been over 1600 tests conducted on in-use ORVR vehicles with an average reduction efficiency of 98%. The odometer readings on a large fraction of these vehicles exceeded 100,000 km. US Tier 2 or California LEV II have reduced evaporative emissions by 90%, and US Tier 3 or California LEV III are 98% effective in reducing evaporative VOC emissions. Engine certified gasoline engines have missed a significant opportunity to reduce their VOC emissions, and MECA supports EPA's consideration of extending advanced canisters and ORVR systems to this category of engines and significantly reduce VOC emissions from these engines.

In these comments, we refer to HDGVs as heavy heavy-duty gasoline vehicles (HHDGVs) since almost all HHDGVs are produced in an incomplete configuration. Also, HDGVs between 8,501 and 14,000 lbs. GVWR will be referred to as light heavy-duty gasoline vehicles (LHDGVs). This definition is consistent with the terminology used by EPA in Tier 3.

Today, both complete and incomplete HHDGVs are implementing Tier 3 evaporative requirements, and all complete HHDGVs will have ORVR by 2022 MY. Incomplete HHDGVs are the only class of gasoline motor vehicles without refueling control. There should no longer be implementation concerns and, with the availability of cost-effective control technology, EPA should include ORVR requirements and testing on this final category of on-road gasoline engines to control these VOC and air toxic emissions from HHDGVs.

In response to specific questions for comment, MECA offers the following recommendations:

(1) EPA should pursue ORVR for HHDGVs. With the regulatory developments since 1994, manufacturers have gained significant experience with ORVR technology on all categories of gasoline vehicles, including complete HDGVs and even incomplete LHDGVs, and there should no longer be implementation concerns. Cost-effective ORVR technology is available to control refueling emissions.
(2) OEMs and secondary manufacturers now have 35 model years of experience in working together on measures to ensure that any actions taken by the secondary manufacturer to complete the vehicle do not violate the certificate of conformity or create in-use issues for on-vehicle fuel vapor control systems. This suggests that any concerns have been and can be addressed without added regulatory measures.
(3) ORVR test procedures promulgated in 1994 are fully fit for purpose. It is our view that HHDGVs (complete or incomplete) should be certified for ORVR using the driving cycles and SHED-test procedures of Subpart B. For oversized complete or incomplete vehicles (unable to fit in a SHED), it may be acceptable to allow for an incomplete chassis (in lieu of complete chassis) to be tested in the SHED or for a fuel/evaporative-ORVR system rig to be constructed and tested in the SHED in lieu of the full incomplete chassis.
(4) The concept of allowing for an engineering evaluation as a means for certification may have merit for unique situations as long as the regulatory provisions to demonstrate compliance are adequately prescriptive. If EPA proposes some form of engineering evaluation it should be presented as an option in rare cases where testing is not feasible, including strict production limits, subject to approval by the Administrator.
(5) Under Tier 3, the useful life for HDGV evaporative emissions and LHDGV and complete HHDGV is 15 years/150,000 miles. The same useful life requirement is feasible for ORVR for HHDGVs and should be applied.

Additional gasoline cycles

MECA supports fuel neutral standards and real-world emission reductions. The low load cycle (LLC), RMC and FTP were developed because they represented specific operating windows characteristic of actual truck operation. In fact, the LLC was derived from actual trip segments from datalogged trucks and compiled into a dynamometer cycle that is made-up of real truck operating modes. Gasoline and diesel trucks operate similarly in similar vocations and therefore they should be tested over conditions that are found in real life and which is often off-cycle. PEMS testing has shown that low speed operation can account for as much as 50% of the NOx emissions from a given operating day. As part of the Stage 2 of the CARB low NOx test program, NREL and SwRI were tasked to propose a low load cycle that represents real world operation. The program involved analysis and compilation of operational data from nearly 900 trucks of all vocations and weight classes that were datalogged over their daily duty cycles. The result of this analysis was a low-load (LLC) test cycle at an average power range of about 8% and clearly represents a significant frequency of operation not captured by either the FTP or the RMC cycles.

The technology being demonstrated in the low NOx program is designed to achieve ultra-low NOx emissions at even this very challenging operating condition. The key to meeting these conditions is thermal management and analogous to strategies needed for cold-start operation. Both types of operation require that the aftertreatment is heated quickly to the optimal temperature of the catalyst and heat is retained during idle and coasting. The technologies demonstrated at SwRI have focused on the more challenging cooler, lean exhaust of diesel engines. However, gasoline catalyst can also meet these conditions using similar approaches involving active and passive thermal management strategies that have been discussed previously. Including close-coupled catalysts, CDA, VVA, driven turbochargers, 48V electrical architectures with electrically heated catalysts and advanced catalysts with low light-off temperatures.

EPA is also considering a high-speed steady-state RMC cycle for HD gasoline engines where traditionally manufacturers have calibrated engines for rich operation to protect the catalyst at the expense of high NMHC and CO emissions. As discussed above, catalysts and exhaust architectures can be designed on large V8 engines to achieve ultra-low emissions. The two 2004 V8 engines and aftertreatment systems discussed above were fully aged and tested over the high speed US06 certification cycle and achieved 120 mg/mile of HC+NOx through the use of closed-loop air/fuel ratio control and advanced catalysts. Over the past 15 years, catalysts coating technology has improved significantly to be even more thermally stable in response to downsized turbocharged engines on passenger cars. To demonstrate durability requirements in these close-coupled locations in the exhaust, the catalysts are aged to 1100 ℃ to stress the thermally stable catalysts and supports. High surface area catalyst support materials inhibit sintering of the active precious metals. Advanced thermally stable oxygen storage materials enable stoichiometric operation even during periods of rich conditions used to protect the catalyst. Improved engine calibration can be tailored to control the air/fuel ratio to match the oxygen storage capacity of the catalyst supports. MECA believes that HD gasoline engines and aftertreatment can be designed for the same operating conditions as diesel engines, and the LLC and RMC certification cycles can be applied to HD gasoline engines.

LABORATORY TEST PROCEDURES CAN BE OPTIMIZED TO REFLECT REAL-WORLD OPERATION

Current cold/hot weighting of the FTP is appropriate, but coolant temperature is not a reliable indicator of SCR efficiency

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. Results from this report, which can be found at http://www.meca.org/resources/NREL_HDV_cold-start_operations_study_1119.pdf, provide some insights into the causes for NOx emission reduction challenges due to real world operation (Zhang, Miller, Kotz, Kelly, & Thornton, 2019). Some observations from this work include:

- Cold starts 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.

Low-load cycle for certification

MECA supports the use of the Low Load Cycle (LLC) for future engine certification. As discussed above, this cycle was developed from real-world activity data that represents urban tractor and vocational vehicle operations characterized by low loads. MECA supports the adoption by EPA of CARB's proposed LLC, which is currently proposed to be LLC candidate #7 as of the submission of these comments. It should be noted that CARB evaluated several candidates for the LLC, and MECA supports EPA and CARB harmonizing on the selection of the final candidate. The purpose of this supplemental certification cycle is to address a known deficiency of certification cycles in validating emission control at low loads. This occurs because the current certification cycles include the FTP and RMC, which have average cycle loads of 27% and 54%, respectively. Furthermore, real-world heavy-duty vehicle operational data confirms that vehicles operate for sustained periods of time at loads below 20%, and current engines and aftertreatment designs are challenged to meet NOx limits during low load operation.

MECA supports the adoption of a federal certification limit for the LLC that aligns with the limit proposed by CARB for MY 2027 engines. As of the submission of these comments, CARB is considering setting the LLC limit at one to three times the FTP limit for MY 2027 and later engines. An LLC limit in the range being considered by CARB can be achieved through the application of engine thermal management and advanced aftertreatment technologies described in the technology section above as well as in MECA's white papers (MECA, 2019; MECA, 2020). Modeling results presented in MECA's white papers indicated the ability to achieve 0.075 g/bhp-hr over the LLC. It should be noted that this modeling result was based on a preliminary engine calibration provided from SwRI's work on the low-NOx demonstration test program. Several revised calibrations have been explored in that test program, since MECA conducted its modeling. Preliminary results from recent engine testing over the LLC show the capability of achieving limits below 0.05 g/bhp-hr with no increase in CO_2 emissions. LLC cycle emission levels are dependent on engine and aftertreatment calibration including implementation of thermal management strategies, and MECA believes more optimization over this cycle will occur as OEMs gain experience with it.

MECA supports the adoption of an idle test procedure and accompanying standard for diesel engines that is aligned with CARB's proposed idling limit of 10 g/hour NOx. The low-load test procedure should be designed to allow for the accurate demonstration and calculation of benefits for technologies such as CDA, driven turbos and stop-start systems, which may not be appropriately credited by testing on the FTP and RMC cycles.

Electrified powertrain testing

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 battery electric, fuel-cell electric and electrified hybrid 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. MECA supports these considerations and has submitted comments to EPA on their HD Phase 2 GHG technical amendments to develop procedures for testing hybrid powertrains to accurately assess their GHG reducing capability. We believe a similar approach can be used to measure NOx emissions and allow electrified technologies to be recognized under the CTI rule for their NOx reduction contribution. Testing should accurately account for these emission reduction benefits since the engine dynamometer ignores the contribution of other powertrain components like transmissions and e-axles. We believe that the method that EPA intends to adopt in these amendments will be a useful tool for mild-hybrid as well as full hybrid powertrains.

Electric trucks and buses are being demonstrated around the world and numerous fleets have adopted the all-electric technology. MECA members that are providing the battery and fuel cell components, electronic controls, transmissions and motors for these applications have made significant investments in developing and commercializing the components that go into electric trucks. MECA supports the early introductory use of incentives to promote innovative technologies during their market introduction. However, in order for a technology to be a sustainable and durable solution, it must demonstrate the ability to compete on the same basis with other technologies to allow consumers the choice that meets their needs and meets performance-based standards. We believe that zero emission technologies are incentivized by ignoring upstream emissions in their fleet average accounting of CO_2 emissions. NOx reductions could be treated on a level playing field with other NOx reducing technologies and averaged through an ABT program for NOx.

SENSOR TECHNOLOGY DEVELOPMENT MAY ENABLE STREAMLINED COMPLIANCE AND HEAVY-DUTY INSPECTION AND MAINTENANCE

On-Board Emission Monitoring and Reporting as a Compliance Tool

MECA supports EPA's consideration of sensors already on vehicles as part of the OBD system to monitor the NOx emissions from trucks over their operating lives. MECA members provide their customers with the full spectrum of temperature, NOx, ammonia, PM and numerous other sensors and OBD control units to allow them to comply with CARB's HD-OBD requirements. Beginning in 2022, CARB has instituted their Real Emissions Assessment Logging (REAL) requirements to store NOx and CO_2 emissions information on the vehicle and report to CARB staff periodically. MECA members offer telematics capability that could be combined with robust sensor monitoring to provide real time reporting. On-Board Monitoring (OBM) has been adopted by China beginning in 2023 and this will be combined with telematics to report emissions and OBD information in real time to the regulators. Beijing Environmental Protection Bureau has instituted a demonstration program on 50,000 trucks operating in the city to require OBM and telematics to report OBD information to the agency. All OBD functions are monitored in real time including NOx, DPF back-pressure, urea quality along with the normal engine operating parameters collected by the OBD system. A GPS installed on each truck monitors vehicle location and all data is stored for up to a year. Currently the system is being used only for monitoring and demonstration, however the agency will begin using it for enforcement before 2023 when it will be mandated nationally. If an emissions or OBD problem is identified, the truck owner will be notified that they must fix the issue.

In anticipation of tighter emission standards and longer durability requirements for heavy-duty trucks, manufacturers are improving the accuracy and durability of their sensors (Kawamoto, et al.). NOx sensors only operate above an exhaust temperature threshold to prevent water condensation and thermal shock of the ceramic element. This may make it difficult to measure NOx during low load and low speed operation. Manufacturers are developing more durable sensor designs and experimenting with sensor placement in the exhaust to minimize these limitations and extend the temperature range of their sensors and improve their durability. MECA supports CARB's decision to hold current NOx sensor OBD thresholds until 2027 when the lowest NOx limits will come into force. Any further tightening of thresholds must consider sensor accuracy, detection limits, and warranty cost implications of the proposed threshold reduction.

MECA supports EPA's consideration of OBM as a potential compliance tool in the future to ensure that trucks are meeting their emission limits over their entire useful life and over all duty cycles. We believe this is a critical tool that represents how compliance will be monitored in the future. It reduces the testing burden for OEMs required to use Real Driving Emissions methods in Europe, China, and India in the near future and offers regulators visibility on an entire fleet of trucks rather than just a handful of selected vehicles. MECA and EPA are participating in the EMTC sensor task force project at SwRI that is characterizing the sensor accuracy and capability to measure at ultra-low NOx levels that are 90% below current tailpipe concentrations. MECA is also a member of the On-Board Sensor Monitoring and Reporting Consortium (OSAR) along with EPA, CARB, SCAQMD, EMA and manufacturers. This program will evaluate emission monitoring and telematic reporting and sensor durability to assess their suitability for long-term compliance assurance.

HEAVY-DUTY IN-USE COMPLIANCE

Moving Average Windows with fixed time windows binned by CO_2

The Not-to-Exceed (NTE) protocol is used to compare the results of portable emission measurement system (PEMS) test data collected by OEMs and EPA for Heavy-Duty In-Use Testing (HDIUT). PEMS data are compared to the NTE limit, which is defined as 1.5 times the engine certification limit plus an instrument accuracy allowance of 0.15 g/bhp-hr. In order to determine compliance with the NTE limit, an OEM must calculate the average emissions of each valid NTE event measured during HDIUT. A test is considered to pass if a minimum of 90% of time-weighted NTE events result in emissions below the NTE limit. The largest flaw in the NTE approach is the determination of valid NTE events. In-use data can be invalidated if any one of several predefined conditions is not met during testing. Data is considered to be invalid when any one of the following occurs: engine torque is less than 30% peak torque, engine power is less than 30% peak power, exhaust gas temperature is less than or equal to 250°C, amongst others. A duty cycle that results in no valid NTE points is still considered as passing in-use compliance.

ICCT published a report in November 2019 that presented in-use test data for several heavy-duty trucks and compared the NTE results to real-world NOx emissions (Badshah, Posada, & Muncrief, 2019). Because of the allowable exclusion of PEMS data, ICCT found that the current NTE protocol evaluates under 10% of the total data collected from in-use operation. In turn, the actual NOx emissions were much higher when including all of the data. Specifically, the NOx emissions from low-speed operation were found to be on average five times the certification limit for the vehicles tested. The same vehicles were able to meet the compliance limit at high speeds.

CARB and EPA have considered eliminating the current NTE protocol in favor of the moving average windows (MAW) approach that is used in Europe. However, while European trucks have been found to meet their NOx emission standards in-use, there remain some deficiencies in Europe's in-use compliance approach. The European MAW protocol allows for exclusion of data when engine power is less than 10% of peak power. The currently proposed LLC #7 has an average power of 7% of peak, which would result in certification to a cycle that is not able to be accurately checked by HDIUT if the European protocol were adopted. The European protocol sets window size based on work. However, if low power operation is included in the evaluation, the emission result for a given window will grow infinitely large as work approaches zero. In addition, setting the window size based on a fixed amount of work results in very long windows during periods of idle and low-load operation where little work is done, which can result in overweighting the emissions at low-load.

For these reasons, MECA supports fixed-time windows that are binned based on CO_2 emissions. MECA suggests retaining the requirement that test vehicles be driven by a real-world fleet driver and on a real-world route. MECA supports EPA and CARB coordinating on HDIUT methods and performance calculations. Finally, MECA asks that EPA consider how stop-start technology will be properly evaluated by HDIUT, including the potential to concatenate data prior to and after engine shut-off events or invalidating longer shut-off events.

Requiring PM measurement for in-use compliance

EPA requests comments on the need to measure PM emissions during in-use testing of DPF-equipped engines. MECA believes that all emission control devices need to be properly functioning over the entire life of heavy-duty trucks, and the DPF is a critical device for the control of PM. In 2015, CARB conducted an extensive study of in-use trucks in California, equipped with DPFs either by the OEM or retrofitted, to try and understand the extent to which these DPFs may be compromised in the field. They found that on the order of 10% of in-use DPFs either had issues or fleets have reported problems with their DPFs. That number has been reduced substantially from 35% in 2007, when DPFs were first required on trucks, to less than 4% in 2011. CARB found that the vast majority of these issues resulted from upstream failures with engine components or operator related errors associated with improper filter regeneration. Because there is the opportunity to accelerate the deterioration of DPFs through improper maintenance of the engine or filter, we believe that it is appropriate to include a compliance procedure to assess the DPF performance. Measurement techniques have improved significantly over the past 10 years for the measurement of PM and particle number (PN).

The real time PN techniques being considered for Periodic Technical Inspection (NPTI) testing have become very compact, cost effective and reliable to check the integrity of the DPF. Testing by the European Joint Research Center (JRC) shows a moderate correlation between emission levels during the type approval cycle (NEDC/WLTC) and low idle emissions even with SPN-PEMS instruments. The scatter further increases when first generation NPTI instruments are included. Any low idle limit has to take into account this scatter, but these results suggest that the technical specifications of NPTI instruments should have acceptable uncertainty, with low cost.

The Netherlands and Germany have already started programs that would eventually lead to the adoption of mandatory NPTI emission testing requirements. NMI, the Dutch metrology institute, has released a draft International Recommendation with the specifications of the PTI particulate number counter. A test procedure and correlation would have to be developed to allow for these compact instruments to be used for compliance purposes.
The test is likely to be a 30 second measurement at low idle speed as a way to confirm the DPF/GPF has not been compromised. In 2016, CARB funded a study at NREL that looked at the PM emissions from DPFs that have been intentionally compromised using opacity and PM measurement on the dynamometer. The results of the measurements were correlated and showed that a 5% opacity was approximately equal to the 10 mg/bhp-hr PM limit (Ragatz & Thornton, 2016).

ENGINES AND AFTERTREATMENT SHOULD BE REMANUFACTURED AS A SYSTEM

Because of their impressive durability characteristics, it has been common to rebuild diesel engines after a million miles and put them back on the road for a second life. Aftertreatment systems have only been on diesel engines for 10 years and OBD systems since 2013. MECA supports the rebuilding of the engine if it can continue to serve the owner. However, if that truck comes with an aftertreatment and OBD system, it is reasonable to ask the rebuilder to download the OBD fault codes before the engine is removed from the chassis. Towards the end of its operating life, the engine is likely to be emitting high PM levels due to wear of the piston rings, worn fuel injectors or a leaky turbocharger. It is impossible to know what upstream conditions the aftertreatment was exposed to prior to the engine rebuild and if it has been compromised. The OBD system on MY2013 and newer trucks can provide an easy to read fault code of the emission critical parts. If catalyst, filter or urea system related codes are present, the aftertreatment and failed components should be replaced with new OEM or aftermarket components. After the rebuilt engine is installed back in the chassis, the OBD codes should be checked to make sure they are cleared. This will ensure that the truck continues to operate as close to certified emission levels as possible.

MECA SUPPORTS PHASED IN USEFUL LIFE AND WARRANTY EXTENSIONS AT THE NATIONAL LEVEL

EPA has indicated that the CTI NPRM may propose an extension of the useful life of heavy-duty engines and aftertreatment. CARB has had several workgroup meetings discussing this topic, and MECA has provided extensive input into the process. We believe that extending the mileage useful life beyond where it is today should be done in stages to allow suppliers the ability to evaluate the impact on their business and design parts with longer durability and useful life. For a class 8 tractor, CARB has proposed a first UL increase in 2027 to 600K miles, and a second increase in 2031 to 800K miles. Suppliers have not tested their parts out beyond the current useful life mileages, nor do they have access to field parts beyond the current warranty period, we believe that such a phase-in would provide an opportunity to design additional durability into emission critical components. MECA members manufacture durable parts according to the specifications demanded by their customers, the OEMs, as part of individual business agreements. The individual component specifications provided to the supplier may not include a correlation between the specification and how that relates to mileage durability on the vehicle. MECA believes that a phase-in approach would allow the advanced technologies to be installed on the trucks by 2027 and provide additional time for suppliers to work with their customers to further extend the durability and useful life.

In conjunction with extending the useful life, EPA should review the current list of emission critical parts and scheduled replacement and maintenance intervals. Validation of the revised replacement intervals will take time to develop with component suppliers.

Aftertreatment parts deterioration can be accelerated through well-known means such as engine exhaust exposure at higher temperature and higher oil consumption to represent longer hours of operation as described in the DAAAC protocol developed under a consortium at SwRI. Wear of on-engine emission critical parts such as EGR, turbochargers or CDA is not able to be accelerated and must be run for the full duration of the useful life period. Understanding the wear mechanism is also more challenging because parts are rarely returned in their used state, but only after failure when it may be difficult to assess how deterioration progressed over the life of the part. There is also no way to properly account for and/or accelerate the years of useful life, as this may be reached in many different types of duty cycles and environments, so MECA supports EPA's intention in the ANPR to not increase the years of useful life beyond the 10 years currently required. We believe that CARB and EPA should align on a reasonable mileage useful life and warranty of emission control parts.

Appropriate Longer Warranty Period

The agency has indicated an intention to propose longer emissions warranty periods. MECA agrees that the current 100,000 mile or 5-year warranty is not representative of how long engines last when compared to the warranty of light-duty passenger cars relative to their useful life. Suppliers are challenged to know how the longer warranty will impact their costs because suppliers do not have available to them the full extent of parts failure and durability information that is available to the OEMs through their dealer networks beyond the current warranty. In fact, many component suppliers have limited visibility on parts that are replaced between the current 100,000 mile warranty period and the full useful life. This presents a challenge for suppliers to project how long their parts are lasting in the field. Furthermore, when suppliers receive parts returned under warranty, they are frequently accompanied by very little information on the diagnosis made by the repair technician. In some cases, a supplier finds that the part is working fine even though a technician has decided to remove and replace it due to insufficient time available to properly diagnose the root-cause of the failure. Repair shops are often under extreme pressure to fix a malfunctioning vehicle so that the owner can return the vehicle to operation. Sometimes, false MIL lighting results in a working part being replaced prematurely. Some malfunctions that result in the illumination of the MIL are due to failure of an upstream part in the engine that results in a downstream component failure and fault code. However, a complete diagnosis of the root cause may take more time than an operator is willing to spend, which can result in a hasty diagnosis by a repair technician. Since the parts will be assumed to be covered under warranty, the technician will default to replacement of all parts that may be responsible for a fault code. Truck manufacturers and parts suppliers will then be responsible for determining if the correct repairs were made and whether the OEM or supplier will cover the associated costs. This postmortem analysis and negotiation can take significant time and resources on the part of suppliers. Because of the lack of existing information, MECA recommends a phase-in for longer warranty similar to that for useful life so suppliers can understand the cost impacts and build them into their business models.

MECA urges EPA to retain an hours of use limit for vocational vehicles because some applications may operate for thousands of hours prior to reaching the mileage or yearly threshold. Some trucks operate at low-speeds for short routes over the course of a work day, including frequent times of engine idling. Others are operated while the vehicle is stationary and the engine is used to power certain functions (e.g., utility trucks). Over the course of a vehicle's life, this results in the engine operating for many hours while the odometer may not reflect this in terms of distance driven. For comparison, heavy-duty off-road equipment, such as construction vehicles, operate in a similar manner, which is why they are generally equipped with hour meters, and owners log the hours instead of mileage of these equipment. MECA suggests that EPA retain the concept of an hour limit to account for high use low-mileage vehicles. We recommend that the hourly warranty limit increase be proportional to the increased mileage limit being proposed based on real-world average speed.

At this time MECA believes that heavy-duty hybrid trucks and components should not be included in the final warranty extension due to the limited experience and number of hybrid powertrains in the market. As market penetration grows and suppliers begin to understand the component durability, they can be incentivized to build more durable parts by introducing a longer warranty on hybrid trucks.

We believe that OBD thresholds and warranty are directly related since an OBD MIL activation during the warranty period will likely lead to a repair as part of a warranty claim. Lower threshold limits could result in an increased number of false MIL events, leading to increased warranty costs. We support CARB's proposal to freeze the OBD thresholds for emission critical parts at current levels through 2027. This is an important consideration under the proposed extended warranty extension and simultaneous introduction of more stringent emission limits. Since the NOx OBD threshold is represented as the FTP emission limit + 0.2 in g/bhp-hr and the HD-OBD regulation is amended every 3-4 years, we recommend that any future proposal to change the OBD thresholds should include a review of the cost implications of such a change in light of any adopted longer warranty requirements.

Another industry that will be adversely impacted by longer warranty and should be included in the impact analysis includes manufacturers of aftermarket replacement parts for heavy-duty vehicles. The longer warranty requirements will have a negative impact on these aftermarket parts manufacturers due to the requirement that aftermarket parts may not be installed on vehicles that are currently under warranty. In most cases, aftermarket parts suppliers have responded to the market need for durable cost-effective replacement parts to help vehicle owners affordably maintain their vehicles. The availability of certain aftermarket parts will likely decrease if manufacturers of these parts are unable to recover the investment needed to develop, manufacture and market them. Aftermarket suppliers will be adversely impacted by the proposed long warranty mileages, and this impact should be considered as part of the economic assessment of the warranty provision. Lower warranty miles would allow owners to repair their vehicles with less expensive aftermarket parts after the warranty expires. This would also reduce the amount of time that OEMs would have a monopoly on replacement parts and retain a competitive third-party aftermarket industry.

MECA believes that an inspection and maintenance (I/M) program is the most effective way to ensure that repairs are made since it is mandatory for registration renewal. Timely engine and aftertreatment maintenance also extend the health of the engine and emission controls and reduce the total cost of ownership. We believe that a HD I/M program tied to vehicle registration is a cost-effective tool to reduce emissions for these reasons:

1) Tying the repair with registration is a better enforcement mechanism than even warranty to ensure the repair is made.
2) I/M encourages a competitive market for cost effective aftermarket parts and a healthy replacement parts industry.
3) Relying on I/M for repairs rather than long term warranty drives down the total cost of ownership for end-users by allowing repairs to be made using competitively priced, equally effective aftermarket parts.

Longer warranty periods ultimately shift the responsibility from the end user to the truck manufacturer to cover the costs of replacing emission critical parts. Proper maintenance is critical in controlling the costs of warranty. An I/M program is the most effective way to ensure that emission controls are maintained and remain on vehicles and continue to function properly to deliver the expected emission benefits.

MECA has had extensive discussions on the topic of longer warranty with CARB staff and we encourage that the agencies coordinate on the length of warranty on a national level that delivers the right balance between cost and emission reduction benefit. Because the cost of warranty is ultimately shifted to the truck owner, some consideration for the up-front cost must be justified by the emission benefit. Please refer to the analysis on page 19 above and in our 2027 technology white paper for incremental costs associated with extended durability and warranty requirements (MECA, 2020). In the case of a Class 8 line-haul tractor that may go through several owners and duty-cycles before it is retired the first owner may not be able to recover the full cost of the warranty from the second owner. MECA agrees that there may be some creative approaches to structuring a long-term warranty.

MECA does not support different warranty periods for some emission related components versus others. However, we would be in favor of a phase-out approach where the warranty cost would transfer to the owner as the vehicle enters the second and third ownership phases. Typically, a new vehicle will be part of a rental or private fleet for about 5 years and then be sold to a second owner. A 10-year warranty would be part of the cost of a new vehicle and the entire cost burden would be on the first owner. As a way to limit the impact of a long warranty on the cost of a new vehicle, EPA could consider a phase-down approach to warranty. For example, for the first 5 years/300,000 miles for a Class 8 truck, the OEM warranty would cover 100% of the cost of repairs, and then for the next 5 years/300,000 miles the OEM warranty would cover 50% of the cost of repair, and the remaining 50% would be the responsibility of the truck owner. Similarly, some fleet owners may prefer the option of purchasing an independent extended warranty for the full coverage.

FUELS: SHIFT BETWEEN GASOLINE/DIESEL, QUALITY AND DURABILITY

Potential fuel shift

EPA asks about the likelihood that the market could experience a shift from diesel engines to gasoline engines as a result of stringent HD diesel standards. MECA supports fuel neutral standards and if the standards for one fuel are disadvantaged with respect to cost in the market, a shift is likely to happen to reduce costs if the technology differences are not justified by the cost. Gasoline engines don't have to be as durable as diesel engines because they require lower ignition pressures, and stoichiometric operation requires less expensive TWC catalysts that can achieve very low NOx reduction without the need to use urea. In some applications such as medium-duty box trucks where the durability and longer useful life of a diesel engine may not be needed, a shift may be observed. This may also be true in medium duty applications where OEMs have the choice of engine certification or a chassis certification under Tier 3 standards. A 20 mg/bhp-hr NOx limit on an engine certification is much lower than the same engine certified as part of a chassis. EPA should anticipate that these fuel shifts are likely to occur and revise the chassis certified limits for these 10,000-14,000 lb weight categories of vehicles.

Impacts of Fuel Quality on Future Aftertreatment Systems

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 affect 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 sulfur effects on 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 and variable valve actuation (VVA) strategies.

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 and MECA. 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 may be on the close-coupled SCR since this is closest to the engine and sees the highest temperature and the major portion of lube oil metal exposure. The downstream, underfloor SCR is somewhat protected from fuel metals by the DOC and DPF. However, it will see higher temperatures during DPF regeneration.

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 include 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 exhaust 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 on today's trucks 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). The metal content of B100 from field samples analyzed by researchers at NREL (https://www.nrel.gov/docs/fy19osti/72341.pdf , https://www.nrel.gov/docs/fy13osti/57662.pdf) have shown metal content far below the current specification for the vast majority of samples collected, and the impurity level has been coming down over the sample years in 2013 and 2019.

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 CTI, 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. We believe this is a critical need that exists for gasoline engines but is currently not broadly accepted for diesel engines.

MECA supports more stringent certification of fuel additives that contain metals including evaluating their potential impact on aftertreatment components. With respect to alternative fuels, MECA has always maintained a fuel neutral position. Fuels such as CNG or LNG are able to meet ultra-low NOx levels when operated in stoichiometric mode with the use of advanced three-way catalysts. Several natural gas engines have already certified to ultra-low NOx levels of 0.02 g/bhp-hr through CARB's voluntary low NOx certification pathway. Although no diesel engines have yet been certified to the same NOx emissions under this program, as we discussed in the technology section above, it would be feasible for engine manufacturers to comply with a 2024 FTP limit of 0.05 g/bhp-hr with existing system architectures through the application of improved catalysts and substrates being offered commercially by MECA members. The engine and aftertreatment hardware being tested in the CARB low NOx program are demonstrating 0.02 g/bhp-hr NOx over the FTP cycle, bringing them on par with the certification limit of the cleanest CNG engines. Under a future low NOx CTI rule, any engines that certify to the standard ahead of 2027 could qualify for early compliance credits if that option were available under the final rule, as discussed below.

ALTERNATIVE APPROACHES TO INCENTIVIZE EARLY REDUCTIONS

MECA supports approaches for early compliance through early introduction of technologies on engines that reduce NOx below a future FTP and LLC limit. CARB has stated that they will introduce an interim FTP standard of 0.05 g/bhp-hr and LLC standard of 0.2 in 2024 and a final standard in the range of 0.015-0.03 g/bhp-hr in 2027 with accompanying LLC of one to three times the FTP standard. EPA will not promulgate their HD FTP and LLC standards until 2027. We believe that early compliance with these final standards should be credited as long as the emission reductions can be verified and enforced. Early compliance credits have been used before as part of regulations to offer incentives for OEMs to bring technologies to the market ahead of schedule. As we have discussed in our 2024 technology whitepaper, significant reductions are possible through engine calibration and substitution of the latest catalysts into today's aftertreatment architectures (MECA, 2019). The value of these credits should be proportional to the performance of the technology below the standard. Since EPA will not have an LLC cycle certification until 2027, engine manufacturers could certify through CARB's 2024 program that will have the LLC and MAW in-use compliance process. The agencies could agree to certification reciprocity for federal credits until EPA's regulation is implemented. Battery electric or fuel cell electric commercial vehicles should be incentivized through advanced technology credits similar to the Phase 1 HD GHG standards. These credits would help to support continued development, optimization and testing of efficiency technologies to deliver cost-effective NOx reductions as part of this regulation.

CONCLUSION

In conclusion, MECA appreciates EPA seeking comment through this ANPR for the Cleaner Trucks Initiative. This is an important first step toward the development of a robust rulemaking that has the potential to result in cost effective air quality benefits for millions of Americans living in nonattainment areas. MECA believes that an FTP limit of 0.02 g/bhp-hr is a technically achievable final standard for a national program by 2027. Low load testing on engine and reaction modeling has shown that thermal management technologies, current generation catalysts and close-coupled aftertreatment can achieve below 0.075 g/bhp-hr in these challenging real-world operating conditions. Our industry is prepared to do its part and deliver cost-effective and durable advanced emission control and efficiency technologies to the heavy-duty sector to assist in simultaneously achieving lower GHG and NOx emissions, while also meeting other criterial pollutant standards.

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REFERENCES

40 CFR Parts 69, 80, and 86. (2001). Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements. *Federal Register*, 5002-5193.

Allen, C. M., Joshi, M. C., Gosala, D. B., Shaver, G. M., Farrell, L., & McCarthy, J. (2019). Experimental Assessment of Diesel Engine Cylinder Deactivation Performance During Low-Load Transient Operations. *International Journal of Engine Research*. doi:https://doi.org/10.1177/1468087419857597

Anthony, J. W., & Kubsh, J. E. (2007). The Potential for Achieving Low Hydrocarbon and NOx Exhaust Emissions from Large Light-Duty Gasoline Vehicles. *SAE Technical Paper 2007-01-1261*. doi: https://doi.org/10.4271/2007-01-1261

Badshah, H., Posada, F., & Muncrief, R. (2019). *Current State of NOx Emissions from In-Use Heavy-Duty Diesel Vehicles in the United States*. Retrieved from https://theicct.org/sites/default/files/publications/NOx_Emissions_In_Use_HDV_US_20191125.pdf

Bunting, B., More, K., Lewis, S., & Toops, T. (2004). Exhaust Phosphorus Chemistry and Catalyst Poisoning. *2004 Department of Energy Diesel Engine Emissions Reduction Conference.*

CARB. (2015). *Draft Technology Assessment: Heavy-Duty Hybrid Vehicles*. Retrieved from https://ww3.arb.ca.gov/msprog/tech/techreport/hybrid_tech_report.pdf

CARB. (2017, June 20). *Carl Moyer Program Guidelines*. Retrieved from CARB Web site: https://www.arb.ca.gov/msprog/moyer/guidelines/current.htm

CARB. (2019). *California Air Resources Board Staff Current Assessment of the Technical Feasibility of Lower NOx Standards and Associated Test Procedures for 2022 and Subsequent Model Year Medium-Duty and Heavy-Duty Diesel Engines*. Retrieved from CARB Web site: https://www.arb.ca.gov/msprog/hdlownox/white_paper_04182019a.pdf

CARB. (2019, January 23). *Heavy-Duty Low NOx Program Workshop: HD UL & Step 2 warranty*. Retrieved from CARB website: https://www.arb.ca.gov/msprog/hdlownox/files/workgroup_20190123/04-HD_UL_&_Step_2_warranty_WS01232019.pdf

Hendrickson, C. S., Upadhyay, D., & Van Nieuwstadt, M. (2017). Selective Catalytic Reduction Control with Multiple Injectors. *SAE Technical Paper 2017-01-0943*. Detroit: WCX17: SAE World Congress Experience. doi:10.4271/2017-01-0943

Hu, S., Howard, C., Quiros, D., Ianni, R., Sobieralski, W., Ham, W., . . . Huai, T. (2019). Overview of CARB's Truck and Bus Surveillance Program (TBSP): Findings and Implications. *29th CRC Real World Emissions Workshop*. Long Beach.

Joshi, M., Gosala, D., Allen, C., Srinivasan, S., Ramesh, A., VanVoorhis, M., . . . Koeberlein, E. D. (2018). Diesel Engine Cylinder Deactivation for Improved System Performance over Transient Real-World Drive Cycles. *SAE Technical Paper 2018-01-0880.* doi:https://doi.org/10.4271/2018-01-0880

Kawamoto, Y., Todo, Y., Shimokawa, H., Aoki, K., Kawai, M., & Ide, K. (n.d.). Development of High Accuracy NOx Sensor. *SAE Technical Paper 2019-01-0749.* doi: https://doi.org/10.4271/2019-01-0749

Khalek, I., Badshah, H., Premnath, V., & Brezny, R. (2018). Solid Particle Number and Ash Emissions from Heavy-Duty Natural Gas and Diesel w/SCRF Engines. *SAE Technical Paper 2018-01-0362*. doi:https://doi.org/10.4271/2018-01-0362

Kruger, M., Bareiss, S., Kufferath, A., Naber, D., Ruff, D., & Schumacher, H. (2019). Further Optimization of NOx Emissions Under the EU 6d Regulation. *Stuttgart International Symposium on Automotive and Engine Technology*. Stuttgart, Germany.

Lance, M., Wereszczak, A., Toops, T. J., Ancimer, R., An, H., Li, J., . . . McCormick, R. L. (2016, October 17). Evaluation of Fuel-Borne Sodium Effects on a DOC-DPF-SCR Heavy-Duty Engine Emission Control System: Simulation of Full Useful Life. *SAE International Journal of Fuels and Lubricants, 9*(3), 683-694. doi:10.4271/2016-01-2322

MECA. (2019). *Technology Feasibility for Model Year 2024 Heavy-Duty Diesel Vehicles in Meeting Lower NOx Standards.* Retrieved from http://www.meca.org/resources/MECA_MY_2024_HD_Low_NOx_Report_061019.pdf

MECA. (2020). *Technology Feasibility for Heavy-Duty Diesel Trucks in Achieving 90% Lower NOx Standards in 2027.* Retrieved from http://www.meca.org/resources/MECA_2027_Low_NOx_White_Paper_FINAL.pdf

Navistar. (2016). *Final Scientific/Technical Report for SuperTruck Project: Development and Demonstration of a Fuel-Efficient, Class 8 Tractor & Trailer Engine System.* Retrieved from https://www.osti.gov/servlets/purl/1460104

Neely, G., Sharp, C., Pieczko, M., & McCarthy, J. E. (2020). Simultaneous NOX and CO2 Reduction for Meeting Future CARB Standards Using a Heavy-Duty Diesel CDA-NVH Strategy. *SAE International Journal of Engines, 13*(2).

Posada, F., Chambliss, S., & Blumberg, K. (2016). *Costs of Emission Reduction Technologies for Heavy-Duty Diesel Vehicles.* Washington, DC: International Council on Clean Transportation.

Posada, F., Chambliss, S., & Blumberg, K. (2016). *Costs of Emission Reduction Technologies for Heavy-Duty Diesel Vehicles.* Washington, DC: International Council on Clean Transportation. Retrieved from https://theicct.org/publications/costs-emission-reduction-technologies-heavy-duty-diesel-vehicles

Ragatz, A., & Thornton, M. (2016). *Aerodynamic Drag Reduction Technologies Testing of Heavy-Duty Vocational Vehicles and a Dry Van Trailer, Appendix C.* Retrieved from https://www.nrel.gov/docs/fy17osti/64610.pdf

Sharp, C. (2019, April). CARB Low NOX Development and Demonstration Programs at SwRI Progress Update. Detroit, MI: WCX 19: SAE World Congress Experience.

Sharp, C., Webb, C. C., Neely, G., Carter, M., Yoon, S., & Henry, C. (2017). Achieving Ultra Low NOx Emissions Levels with a 2017 Heavy-Duty On-Highway TC Diesel Engine and an Advanced Technology Emissions System - Thermal Management Strategies. *SAE International Journal of Engines, 10*(4), 1697-1712. doi:https://doi.org/10.4271/2017-01-0954

Sharp, C., Webb, C. C., Neely, G., Sarlashkar, J. V., Rengarajan, S. B., Yoon, S., . . . Zavala, B. (2017). Achieving Ultra Low NOx Emissions Levels with a 2017 Heavy-Duty On-Highway TC Diesel Engine and an Advanced Technology Emissions System - NOx Management Strategies. *SAE International Journal of Engines, 10*(4), 1736-1748. doi:https://doi.org/10.4271/2017-01-0958

Sharp, C., Webb, C. C., Yoon, S., Carter, M., & Henry, C. (2017). Achieving Ultra Low NOx Emissions Levels with a 2017 Heavy-Duty On-Highway TC Diesel Engine - Comparison of Advanced Technology Approaches. *SAE International Journal of Engines, 10*(4), 1722-1735. doi:https://doi.org/10.4271/2017-01-0956

Tanner, C. W., Twiggs, K., Tao, T., Bronfenbrenner, D., Matsuzono, Y., Otsuka, S., . . . Koyama, H. (2015). High Porosity Substrates for Fast-Light-Off Applications. *SAE Technical Paper 2015-01-1009.* Detroit: SAE 2015 World Congress & Exhibition. doi:10.4271/2015-01-1009

U.S. Department of Energy. (2018). *2018 Annual Merit Review Vehicle Technologies Office Results Report.* Retrieved from https://www.energy.gov/sites/prod/files/2018/11/f58/2018%20Vehicle%20Technologies%20Office%20Annual%20Merit%20Review%20Report.pdf

U.S. EPA. (2013, March). *EPA.* Retrieved from https://www.epa.gov/regulations-emissions-vehicles-and-engines/proposed-rule-and-related-materials-control-air-pollution

U.S. EPA. (2016, October 25). Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles -- Phase 2. *Federal Register,* pp. 73478-74274.

U.S. EPA. (2017, May 31). *Impact of Mobile Source Emissions on Air Quality.* Retrieved from EPA: https://www.epa.gov/sites/production/files/2017-06/documents/05312017-epa-presentation.pdf

U.S. EPA. (2017, October 20). *Menu of Control Measures for NAAQS Implementation.* Retrieved from U.S. EPA Web site: https://www.epa.gov/sites/production/files/2016-02/documents/menuofcontrolmeasures.pdf

Walker, A. (2016, September). Catalyst-Based Emissions Control Solutions for the Global HDD Market – What Does the Future Hold? *SAE Heavy-Duty Diesel Emission Control Symposium*. Gothenburg, Sweden.

Williams, A., Luecke, J., McCormick, R. L., Brezny, R., Geisselmann, A., Voss, K., . . . Abi-Akar, H. (2011). Impact of Biodiesel Impurities on the Performance and Durability of DOC, DPF and SCR Technologies. *SAE International Journal of Fuels and Lubricants, 4*(1), 110-124. doi:10.4271/2011-01-1136

Williams, A., McCormick, R., Lance, M., Xie, C., Toops, T., & Brezny, R. (2014). Effect of Accelerated Aging Rate on the Capture of Fuel-Borne Metal Impurities by Emissions Control Devices. *SAE International Journal of Fuels and Lubricants, 7*(2), 471-479. doi:https://doi.org/10.4271/2014-01-1500

Yang, J., Roth, P., Durbin, T. D., Johnson, K. C., Cocker, III, D. R., Asa-Awuku, A., . . . Karavalakis, G. (2018). Gasoline Particulate Filters as an Effective Tool to Reduce Particulate and Polycyclic Aromatic Hydrocarbon Emissions from Gasoline Direct Injection (GDI) Vehicles: A Case Study with Two GDI Vehicles. *Environmental Science & Technology, 52*(5), 3275-3284. doi:https://doi.org/10.1021/acs.est.7b05641

Zhang, C., Miller, E., Kotz, A., Kelly, K., & Thornton, M. (2019). *Characterization of Medium- and Heavy-Duty Vehicle Operations from In-Use Data: An Analysis of Starts, Soak Time, and Warm-Up Duration.* National Renewable Energy Laboratory, Golden, CO. Retrieved from https://www.nrel.gov/docs/fy20osti/74725.pdf

APPENDIX I

Technology Feasibility for Model Year 2024 Heavy-Duty Diesel Vehicles in Meeting Lower NOx Standards

APPENDIX II

Technology Feasibility for Heavy-Duty Diesel Trucks in Achieving 90% Lower NOx Standards in 2027