WRITTEN STATEMENT
OF THE
MANUFACTURERS OF EMISSION CONTROLS ASSOCIATION
ON THE U.S. ENVIRONMENTAL PROTECTION AGENCY'S PROPOSAL TO RETAIN THE OZONE NATIONAL AMBIENT AIR QUALITY STANDARDS
DOCKET ID NO. EPA-HQ-OAR-2018-0279

October 1, 2020

The Manufacturers of Emission Controls Association (MECA) is pleased to provide testimony in response to the U.S. EPA's request for public comment on the Proposal to Retain the National Ambient Air Quality Standards for Ozone (Docket ID No. EPA-HQ-OAR-2018-0279). MECA firmly believes that the emission control technologies for mobile sources that will be needed to help meet the most stringent standards for ozone are cost effective and readily available. Many of these emission control technologies for mobile sources are being used today on on-road and non-road applications in the U.S. and other major marketplaces in the world.

MECA is a non-profit association of the world's leading manufacturers of emission control technology for mobile sources. Our members have over 50 years of experience and a proven track record in developing and manufacturing emission control and efficiency technologies for a wide variety of on-road and off-road vehicles and equipment, including extensive experience in developing emission controls for gasoline and diesel engines and vehicles in all world markets. Our industry has played an important role in the emissions success story associated with mobile sources in the United States, and has continually supported efforts to develop innovative, technology-advancing, emissions programs to deal with air quality problems.

MECA will defer to the health experts to determine the appropriate ozone levels for the ambient standards given that they are not within our area of expertise. The Clean Air Act requires that these standards be set to protect the public health with an adequate safety margin. MECA offers comments here regarding the technological feasibility of emission control technologies for gasoline and diesel engines that are available to meet the EPA proposed standards for NOx and hydrocarbon (HC) emissions, the precursors to ozone, and the even more stringent standards should EPA conclude that lower ozone NAAQS would be needed to protect human health and welfare. A 2013 assessment by WHO's International Agency for Research on Cancer (IARC) concluded that outdoor air pollution is carcinogenic to humans.

While beyond the scope of the health-based decision before the agency, MECA offers comments here to demonstrate there are technologically feasible and cost effective emission control technologies for mobile source engines that are available to meet the most stringent ozone standards under consideration by EPA. MECA commends EPA for periodically reviewing the ozone standards to ensure that the standards are as protective as recommended by EPA's Clean Air Scientific Advisory Committee (CASAC). In 2015, the CASAC concluded that an 8-hour ozone NAAQS set to 60 ppb would be protective of human health.

Mobile Source Regulations that Reduce Ozone

The U.S. EPA has already put in place important regulatory programs for reducing PM and gaseous emissions from on-road and non-road engines and vehicles in both the light-duty and heavy-duty sectors. In addition, the establishment of the North American Emission Control Area (ECA) for ocean-going vessels that call on ports in the U.S., Puerto Rico, and U.S. Virgin Islands is projected to result in significant reductions in PM and NOx emissions. These regulatory programs rely on a systems approach that combines advanced engine technology, the use of low and ultra-low sulfur fuels, and advanced exhaust emission control technologies to achieve, in most cases, 90+% reductions in both PM and gaseous emissions compared to legacy engines and equipment.

New on-road light-duty vehicles are regulated under Tier 3 standards as well as the light-duty GHG and CAFE rules for model years through 2026. Tier 3 creates a national set of criteria pollutant standards for light-duty vehicles by largely harmonizing EPA's Tier 3 emission standards with California's LEV III emission standards, and reduced gasoline sulfur levels to a 10 ppm average across the nation by 2017. A significant difference that remains between the two light-duty regulations is that California mandates a further tightening of the PM standard under LEV III to the 1 mg/mi level beyond 2025 while EPA's Tier 3 has no such provision and retains a level three times higher, 3 mg/mile.

Heavy-duty on-highway engines are currently regulated by the 2007-2010 standards, which have resulted in diesel particulate filters (DPFs) and selective catalytic reduction (SCR) systems being installed on all new heavy-duty on-highway diesel trucks. Heavy-duty truck fuel economy and GHG emissions are regulated via Phase 1 and Phase 2 GHG standards that fully phase in by MY 2027. In August 2020, the California Air Resources Board (CARB) approved more stringent criteria pollutant standards for heavy-duty vehicles, particularly tighter NOx limits, with implementation starting with model year 2024 engines. This "Omnibus" regulation will also cut the current PM limit in half, increase durability requirements, lengthen warranty periods, and add more stringent in-use testing requirements that are more representative of real-world operation. These revisions are expected to result in significant NOx emission reductions throughout California. EPA has also initiated the regulatory development process for its Cleaner Trucks Initiative (CTI), which is likely to include the same provisions adopted by California, and should result in nationwide emission benefits. A harmonized CTI and California Omnibus that create a "One National Program" approach will provide the most cost-effective emission reductions and regulatory certainty to industry.

U.S. Tier 4 non-road diesel emission regulations that have been phased in over the 2008-2015 timeframe have resulted in SCR system installation on all new non-road engines while DPFs are found on only about 40% of the same engines. Recognizing the progress made around the world to reduce PM and NOx emissions from non-road engines and equipment, California recently initiated a test program to demonstrate the feasibility to reduce NOx and PM limits on non-road engines in support of future national standards for these engines. This program is likely to draw on the same types of NOx reduction technologies demonstrated to be cost effective for the on-highway regulations adopted by CARB. We believe that more stringent NOx limits for non-road engines could be achieved, up to 90% lower than Tier 4 final, with currently available technologies and would result in cost-effective emission benefits.

In July 2006, EPA finalized its regulation for new stationary compression ignition internal combustion engines to reduce diesel air pollution emissions. In February 2010, EPA issued its final regulation for existing stationary reciprocating internal combustion engines that would reduce toxic pollution emissions. The technologies discussed in this document for gasoline and diesel engines on vehicles are available and have been proven effective for stationary internal combustion engines. These include DOCs and SCR catalysts as well as DPFs to reduce PM emissions from stationary diesel engines. Three-way catalysts, also known as non-selective catalytic reduction catalysts (NSCR), have been used effectively on thousands of large, natural gas-fueled, reciprocating engines (so-called rich burn or stoichiometric natural gas engines) used for power production or pumping applications. Additional tightening of standards for both existing and new stationary internal combustion engines should be considered in the future to further reduce the HC, NOx and PM emissions that contribute to ozone levels across the country from these stationary engines.

Support for Tighter Heavy-Duty Engine NOx Standards

A technology demonstration program at Southwest Research Institute that began in 2013 is nearing completion. The CARB-contracted program has been enhanced under multiple phases to expand duty cycles, technologies and engines. MECA and our members have committed millions of dollars in cash and in-kind contribution to provide hardware and funding into this program to demonstrate multiple pathways for meeting a 90% reduction in NOx while not increasing GHG emissions and controlling other regulated and unregulated pollutants. This seminal demonstration program also benefited from in-kind contribution from Volvo and Cummins who provided engines and calibration assistance, funding from U.S. EPA, South Coast AQMD, and the Port of Los Angeles, among others, to deliver a robust technology feasibility demonstration through partnership between industry and regulators.

The first stage of the program that concluded in 2016 relied on an advanced MY 2014 diesel engine that included turbocompounding technology for meeting future 2017 Phase 1 GHG limits. Although this engine provides impressive fuel saving at highway speeds, it posed thermal management challenges at cold start and low load operation. This could be overcome through the use of active heating based either on electric or fuel burner components. In spite of these challenges, this first ever demonstration of ultra-low NOx emissions served as a great learning opportunity through screening of thirty-three different aftertreatment configurations and advanced calibration to demonstrate that future 0.02 g/bhp-hr emission limits are feasible. The learning from this stage of the program served as the starting point for technology selection in future stages of this multi-year program. This work was published in 2017 in a number of SAE technical papers (Sharp, et al., 2017-01-0954, 2017-01-0956, and 2017-01-0958).

The primary objective of stage two of the program was to develop a low load certification cycle based on real world truck operation derived from duty cycles collected by the National Renewable Energy Lab (NREL) and UC-Riverside on over 800 trucks operating in California and across the U.S. The methodology developed under this program by NREL and SwRI was a completely original approach to certification cycle development and will serve as a model for future regulations around the world for years to come. The stage 1 engine and aftertreatment system was operated over the newly developed certification cycle and demonstrated that when engine calibration and aftertreatment are optimized for real world operation, it is possible to achieve NOx reductions over 95% from the baseline system under the most challenging conditions. Although overcoming the thermal mass of the turbocompound unit at low loads required active thermal management at a fuel penalty of about 2%, we did learn quite a bit about aftertreatment architecture and design optimization to reduce emissions from both cold-start and low load operation, and this knowhow was carried into stage 3 of the program.

Stage 3 of the program began in 2017 based on a different state-of-the-art 15L engine that met the 2017 Phase 2 GHG limits without the use of turbocompounding. The aftertreatment system options were narrowed down based on all of the learning in stages 1 and 2. Furthermore, replacing the use of active burner thermal management, we applied cylinder deactivation (CDA) on this engine and further calibration to get rapid heat-up of the aftertreatment from cold-start as well as maintaining SCR temperature during coasting, idling and low speed operation. The CDA was further able to provide thermal management while reducing fuel consumption and CO_2 emissions. Other technology options for simultaneous thermal management and GHG reductions were also evaluated and are discussed below. These include driven turbochargers among others that OEMs could employ to meet tighter NOx limits and future Phase 2 standards. This stage of the program was another first of its kind demonstration of achieving both ultra-low NOx emissions and simultaneous GHG reductions that have long been considered a challenging trade-off by engine developers.

Over the course of this multi-year program, the technology innovation was not static, and in fact new technologies came on midstream as they became commercially viable. Even the aftertreatment components that remained fundamentally unchanged from today's systems on trucks benefitted from multiple generations of substrate improvements and new catalyst formulations that occurred over the 7 years of testing under this program. Further improvements in catalyst and architectures are already being contemplated by U.S. EPA as they prepare for their own demonstration testing of similar technologies but incorporating evolutionary improvements on concepts demonstrated in CARB's technology demonstration at SwRI. This example of continual improvement and optimization is a testament to the ongoing innovative technology development occurring in the industry between suppliers and their OEM customers. Each time a test is run, new information is obtained and applied to the next iteration. This has been going on continually over the past 10 years of advanced emission controls on trucks. Our industry has seen a tremendous amount of optimization on both engines and aftertreatment that, in the absence of tighter standards, has been applied to downsize systems by about 60% and reduce their costs by about 30% (costs will be further addressed later).

MECA recently co-funded an emission inventory and air quality modeling analysis based on the emission limit values and durability requirements proposed by CARB to quantify the air quality benefits if a national standard were set by U.S. EPA under the CTI to align with the CARB proposed limits and implementation dates (MECA, 2020; Alpine Geophysics, 2020). The analysis did not incorporate the compliance program changes or warranty revisions into our model assumptions. The foundation of the evaluation was the current U.S. 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 U.S. 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 U.S. 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 U.S. 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.

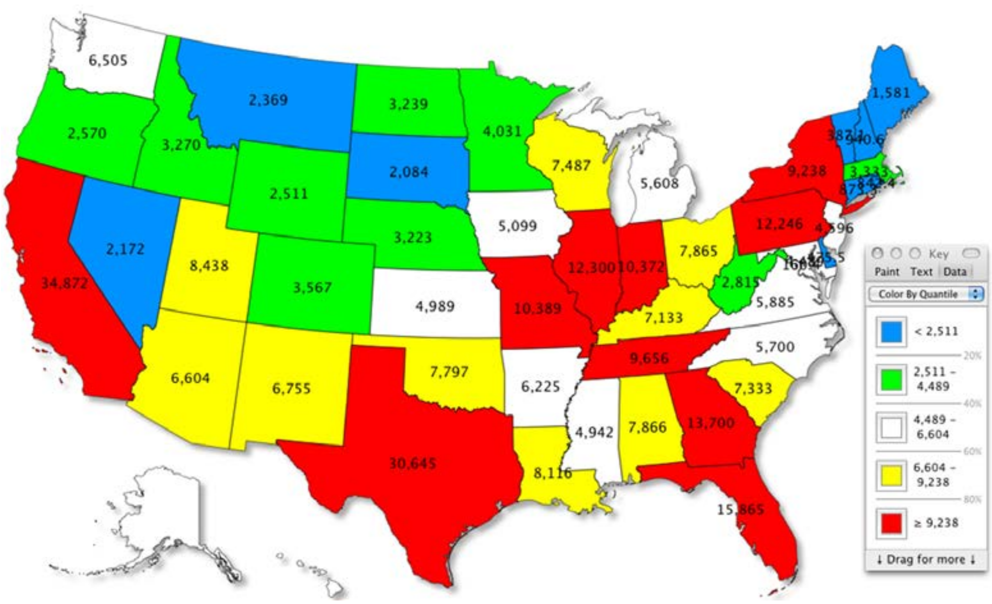

Figure 1. Federal NOx Standard Annual Benefit in 2035 (tons reduced)

Results from the inventory analysis show that the new modeled FTP limits would result in a national reduction of nearly 330,000 tons per year of NOx in 2035. 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. These estimates likely represent 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. U.S. EPA 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 NOx reductions, the proposed standards are projected to yield reductions in VOCs and carbon monoxide in 2035.

The companion air quality analysis concluded that ozone levels would decline in several counties in 2035 as a result of the NOx reductions estimated by the inventory analysis discussed above. The modelled 2028 base year 8-hour ozone design values were found to be above the 70 ppb NAAQS for 75 monitoring locations. Applying the potential CTI strategy to the 2028 base year eliminates ozone nonattainment everywhere east of the Rockies, while several monitoring sites (mostly in California) are projected to have reduced ozone levels yet remain in nonattainment. The greatest ozone reduction impact of the strategy is seen in urban areas and along highway corridors with reductions of up to 6.5 ppb seen in the west (San Bernardino) and 4.9 ppb seen in the east (Atlanta). It is important to note that even though the 2015 ozone NAAQS was finalized at 70 ppb, EPA's Clean Air Scientific Advisory Committee (CASAC) in 2015 supported a range of 60-70 ppb for the 8-hour primary ozone standard. Prior to applying the projected CTI strategy, nearly 300 monitoring sites are projected to have 8-hour ozone design values between 60 and 70 ppb, and the proposed CTI strategy will reduce these by an average of 2.35 ppb and up to a max of 5 ppb.

In support of cost-benefit analyses conducted by CARB as part of the development of the Omnibus, MECA estimated the costs (in 2019$) of meeting an FTP certification standard of 0.02 g/bhp-hr and proposed LLC certification standard in 2027. To meet these tighter standards, the technology evolution (discussed in our white papers referenced herein) includes incremental improvements to substrates and catalysts as well as the addition of a close-coupled SCR and dual dosing system with one heated doser, additional NOx sensors and an ammonia sensor in an upgraded OBD system. In addition, this analysis assumed the use of CDA and an EGR cooler bypass system. All of these technologies have been demonstrated in the CARB Low-NOx demonstration program at SwRI. Two cost estimates were prepared; one that assumed today's durability and warranty requirements, and one assuming longer durability and warranty requirements – 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 – that were initially proposed by CARB (CARB, 2019). Since that time, CARB staff have revised the FUL and warranty requirements to those included in the current Omnibus. Therefore, we expect the cost estimate for longer FUL and warranty provided below to represent a worst-case scenario.

For a vehicle with a 6-7L 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 12-13L 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. The estimated incremental costs to meet the above referenced durability and warranty requirements for a 6-7L engine and 12-13L engine were $1,800 to $2,450 and $2,000 to $2,750, respectively. 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 6-7L engines and $3,550 to $4,800 for 12-13L engines. If a Class 8 truck with 12-13L engine is assumed to sell for an average price of $177,000 in 2027, based on the historical 1% annual rate of increase reported previously, the additional cost of emission controls on this truck will account for roughly 2-2.7% of the total vehicle price. It is important to reiterate that these the cost estimates are biased high since they are based on more stringent requirements than those included in the final Omnibus proposal.

MECA estimated that the proposed NOx 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 replacing a lower-emitting vehicle that operates for less time. U.S. 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).

The ICCT recently conducted an analysis that estimated the cost of diesel emissions control technology to meet the proposed Omnibus standards (Posada, Isenstadt, & Badshah, 2020). Their study included direct manufacturing costs and indirect costs for two engine sizes, but costs of proposed longer warranty requirements were excluded. The methodology follows the steps outlined in previous ICCT cost studies where both in-cylinder technology aftertreatment costs are estimated and scaled to account for engine size (Posada, Chambliss, & Blumberg, 2016). The ICCT concluded that the incremental costs to meet the proposed MY 2024 standards are about $100 to $1,000 for 7L and 13L engines. In order to meet the proposed MY 2027 standards, ICCT estimated both low-cost and high-cost durability cases. The resulting incremental cost range estimated to meet the Omnibus requirements was $1,800 to $2,500 for a 7L engine and $2,200 to $3,200 for a 13L engine. The ICCT results are roughly 10-20% lower than those estimated by MECA, and this may be explained by differences in assumptions for useful life and baseline year for cost between the two analyses.

Exhaust Emission Technologies to Reduce Hydrocarbon and NOx Emissions from Diesel Engines

Due to the long operating lives of many diesel engines, it will take many years for older, "dirtier" on-road and non-road diesel engines to be replaced with the mandated newer "cleaner" engines. Given the health and environmental concerns associated with older diesel engines and because older, existing on-road and non-road diesel engines make up a significant percentage of diesel pollution emitted, there has been interest in retrofitting the existing legacy fleet of on-road and non-road diesel engines as a means of complying with federal or state ambient air quality standards for PM and ozone. MECA believes that proven retrofit technologies are available to deliver significant reductions in HC and NOx emissions from existing on-road and non-road diesel engines. Effective regulatory and/or incentive programs will be needed at the local, state, and federal levels to accelerate the clean-up of older diesel engines through the use of verified retrofit technologies or replacement with newer, cleaner engines.

A number of advanced emission control technologies exist today to significantly reduce HC and NOx emissions from new and existing diesel engines, and most of these are playing a major role in complying with current EPA emission standards for new engines. These include diesel oxidation catalysts (DOC), diesel particulate filters (DPFs), selective catalytic reduction (SCR), NOx adsorber catalysts, and exhaust gas recirculation (EGR). In addition, several proven technologies that have not yet made significant penetration into the diesel engine market, but could do so if more stringent limits are set, include cylinder deactivation, advanced turbochargers, and several advanced aftertreatment designs.

Diesel Particulate Filters – Diesel particulate filters (DPFs) are the most effective PM reduction technology for a wide range of diesel engine applications. Besides reducing PM emissions by up to 90 percent or more, DPFs remove HC emissions by up to 80 percent or more. Millions of on-road heavy-duty vehicles and hundreds of thousands of off-road pieces of equipment have been retrofitted with DPFs worldwide. In addition, MECA members have verified a variety of DPF retrofit technologies with both EPA and CARB. The durability and performance of PM control technologies has been demonstrated on OEM heavy-duty, on-road applications since the 2007 model year when nearly every new medium-duty and heavy-duty diesel vehicle sold in the U.S. or Canada has been equipped with a high efficiency diesel particulate filter to comply with the U.S. EPA's 2007/2010 heavy-duty highway emission regulations. This represents more than two million trucks operating with DPFs here in North America. DPFs have been standard equipment on new heavy-duty trucks in Europe starting from 2013 and China this year (2019 in major cities) in order to comply with the Euro VI and China VI, respectively, diesel particle number emission standards. A number of manufacturers have also started to equip a range of off-road diesel engines with DPFs to comply with EPA's Tier 4 off-road emission standards.

Diesel Oxidation Catalysts (DOCs) – DOC technology is a proven technology that has been employed for decades and has been installed on hundreds of millions of on- and off-road engines worldwide. Control efficiencies of 20 to 50 percent for PM, up to 90 percent reductions for carbon monoxide (CO) and hydrocarbon (HC), including large reductions in toxic hydrocarbon species have been achieved and reported in tests of DOCs on a large variety of on-road and non-road diesel engines. DOCs also play a pivotal role in optimizing the NOx reduction efficiency of the SCR system. The DOC in a diesel exhaust emission control system is designed to optimize the reaction where nitric oxide (NO) is oxidized to nitrogen dioxide (NO_2) to achieve an optimal ratio of NO/NO_2, which helps to maximize the SCR's efficiency.

Selective Catalytic Reduction (SCR) Technology **–** SCR is a proven, durable NOx reduction technology for mobile sources and has become an important NOx emission reduction technology for mobile sources in the U.S. and other world markets as evidenced by the hundreds of thousands of light-duty and heavy-duty vehicles that have been sold and operated with SCR technology for decades in Europe, Japan, and North America. SCR is being used by most engine manufacturers for complying with U.S. EPA's on-road and non-road heavy-duty diesel engine emission standards. Several auto manufacturers have also commercialized SCR systems for light-duty diesel vehicles that are being sold across the U.S.

MECA recently published two white papers that provide detailed information on technology feasibility and cost-effectiveness for future NOx emission regulations. 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).

Manufacturers continue to improve SCR substrates in order to increase geometric surface area, allow uniform catalyst coating, reduce back pressure on the engine, and reduce thermal mass. As OEMs gained experience with engine calibration, catalyst suppliers made improvements to the performance and reduced manufacturing costs. More efficient packaging for thermal management and efficient urea mixing designs have allowed the systems to be reduced in size by over 60% while achieving lower NOx emissions than first generation systems. The cost of a heavy-duty truck has increased at approximately 1% per year (Posada, Chambliss, & Blumberg, 2016) while the cost of emission controls has declined, making emission controls a smaller fraction of new truck cost. Due to the combination of cost savings realized since 2010, as well as the cost reductions expected before new standards are implemented in 2024 and 2027, we estimate that the emission controls needed to meet future 0.02 g/bhp-hr NOx standards in 2027 will cost about the same or less than MY 2010 systems. In full size engine testing at Southwest Research Institute that began in 2015, these advanced aftertreatment technologies have demonstrated the ability to convert over 98% of the NOx to harmless nitrogen and water over all operating modes and duty cycles.

Several MECA member companies have proven experience in the installation of SCR systems for both stationary and mobile engines, as well as the installation of integrated DPF+SCR emission control systems for combined PM and NOx reductions. A number of off-road diesel retrofit demonstrations have been done with combination DPF+SCR retrofit systems. Applying SCR to diesel-powered engines provides simultaneous reductions of NOx, PM, and HC emissions and retrofit manufacturers have verified DPF+SCR or DOC+SCR retrofit systems for both on-road and off-road applications. In some of these applications, DPF+SCR equipped retrofit systems have achieved over 80% NOx reduction. There are hundreds of DPF+SCR retrofit devices operating on medium- and heavy-duty on-road vehicles in Europe and the U.S. Although important differences exist between on-road and off-road diesel applications, many of the same manufacturers develop similar systems for OEM on-road and off-road applications. The experience from on-road applications are typically carried over into more challenging off-road vehicles.

Passive NOx Adsorber Technology **–** 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°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 (e.g., SAE 2017-01-0954 and SAE 2017-01-0958). PNA technology may be one of the strategies available to engine and vehicle manufacturers to achieve lower cold-start tailpipe NOx levels.

Engine Technologies to Reduce Emissions from Diesel Engines

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

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

In addition to affecting the power density of the engine, turbochargers play a significant role in PM, NOx and CO_2 regulations compliance. Continuous improvement in turbocharger technology is making it possible to run very lean combustion (high air/fuel ratios) which is fast and efficient. This allows for very low particulate generation and even low engine-out NOx. In addition, these highly efficient turbochargers affect the pumping loop in such a way that they can provide positive crankshaft work and improve brake specific fuel consumption (BSFC) and brake specific CO_2 ($BSCO_2$) as intake manifold boost pressure becomes higher than exhaust manifold backpressure.

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

Cylinder Deactivation – Cylinder deactivation (CDA) is an established technology on light-duty vehicles, with the primary objective of reducing fuel consumption and CO_2 emissions. This technology combines hardware and software computing power to in effect "shut down" some of an engine's cylinders, based on the power demand, and keep the effective cylinder load in an efficient portion of the engine map without burning more fuel by reducing the number of cylinders firing during lower load operation. The technology uses solenoids on the valve lifters to keep intake and exhaust valves closed when a cylinder is deactivated while simultaneously shutting off fuel to the deactivated cylinder. Rather than pumping cold intake air into the exhaust system during coasting or idling, the valves are closed, allowing the deactivated cylinder to act as a spring as the piston moves up and down the bore. Closing the valves eliminates most of the normal pumping losses that reduce the engine fuel efficiency and thermal energy due to cold air being pumped through the exhaust.

Deactivating a portion of the cylinders causes the remaining active pistons to work harder within a more efficient part of the engine operating regime, thus increasing fuel economy and generating more heat to get the aftertreatment hot faster. In addition, shutting off an engine's cylinders during deceleration and idling reduces air flow through the engine and exhaust to enable heat retention in the exhaust system. Both of these conditions, enabled by CDA, improve the SCR's ability to effectively reduce NOx emissions. During low load operation, CDA has resulted in exhaust temperatures increasing by 50°C to 100°C when it is most needed to maintain effective conversion of NOx in the SCR. In some demonstrations, CDA has been combined with a 48V mild hybrid motor with launch and sailing capability to extend the range of CDA operation over the engine, and this may deliver multiplicative CO_2 reductions from these synergistic technologies.

Electrification – Electrified powertrains are quickly making their way from light-duty passenger cars to commercial trucks and buses. The technology level of electrification and penetration rate can vary across weight classes and vocations, but the conclusion that electrified powertrains are an effective tool to reduce CO_2 as well as criteria pollutants is being recognized by regulators and vehicle manufacturers. There are numerous examples of electric and electrified commercial vehicles being offered for sale and demonstrated by virtually all of the OEMs. Suppliers anticipate that electrification will play a more significant role in helping OEMs meet future NOx and GHG standards.

Various levels of electrification are available, and some are more suited for certain types of vehicle applications and duty cycles. The configurations range from mild hybrids to strong/full hybrids to plug-in hybrids to full battery and fuel cell electric. In all of the configurations that still include an engine, various components are likely to be electrified in future engines and vehicles. These include electric turbos, electronic EGR pumps, AC compressors, electrically heated catalysts, electric cooling fans, oil pumps and coolant pumps among others.

Technologies to Reduce Emissions from Gasoline Engines

Hydrocarbon precursors to ozone formation can be emitted from the tailpipe or volatilized from the fuel system of gasoline vehicles. The technology base of advanced three-way catalysts, exhaust hydrocarbon adsorber materials, high cell density substrates, emission system thermal management strategies, secondary air injection systems, advanced carbon canisters, advanced low fuel permeation materials, and air intake hydrocarbon adsorber materials that have already been commercialized for PZEV gasoline vehicle applications can be extended to and further optimized to allow all light-duty, medium-duty, and heavy-duty gasoline vehicles to achieve the exhaust and evaporative emission reduction needed by vehicle manufacturers to comply with LEV III/Tier 3 light-duty, medium-duty, and heavy-duty vehicle exhaust and/or evaporative emission standards.

MECA believes that regulations should set 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 chassis certified medium-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 ultra-low exhaust emission levels.

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), U.S. EPA tested a 2011 LDT4 pick-up truck with a 5.3L V8 engine that included a MECA supplied aftertreatment system. The aftertreatment consisted of advanced catalyst coating on 900 cpsi substrates in the close-coupled location as well as underfloor catalysts and was aged to 150,000 miles. 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.

We believe that an opportunity exists to significantly reduce VOC emissions from gasoline heavy-duty engines by expanding Onboard Refueling Vapor Recovery (ORVR) to incomplete HDGVs rated over 14,000 lbs. Gross Vehicle Weight Rating (GVWR). The U.S. 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 U.S. 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. U.S. Tier 2 or California LEV II have reduced evaporative emissions by 90%, and U.S. 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 U.S. 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 U.S. EPA in Tier

3. Today, both complete and incomplete HHDGVs are implementing Tier 3 evaporative requirements, and all complete HHDGVs will have ORVR by MY 2022. 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, we believe that ORVR requirements and testing should be applied to this final category of on-road gasoline engines to control these VOC and air toxic emissions from HHDGVs. We encourage EPA to tighten the refueling requirements for this category of heavy-duty gasoline engines under the CTI.

MECA believes that further reductions of hydrocarbon and NOx emissions from the in-use fleet of passenger vehicles can be achieved cost effectively by adopting tighter aftermarket converter requirements for light-duty, gasoline vehicles that set higher performance and durability standards consistent with performance standards required by California for aftermarket gasoline converters since 2009. CARB's regulation eliminates the sale of older aftermarket converter products that have modest performance standards and a limited 25,000 mile warranty, and require that higher performance and more durable OBD-compliant aftermarket converter products be used on both non-OBD and OBD-equipped vehicles since January 2009. Several other states have adopted California's aftermarket converter requirements, including Maine, New York, Colorado, and Maryland. Several others have signaled an intent to move forward, including New Jersey, Connecticut, and Massachusetts.

These CARB-approved OBD-compliant aftermarket converters are warranted for five years or 50,000 miles based on the use of a more aggressive, high temperature accelerated engine-aging protocol compared to the vehicle durability demonstration currently required by EPA for approved aftermarket converter products. EPA has not updated its aftermarket converter requirements since 1986 and with more than three million aftermarket converters sold per year across the U.S. (based on surveys completed by MECA with aftermarket converter manufacturers), significant additional reductions of hydrocarbon emissions, including toxic hydrocarbon emissions, and NOx emissions could be achieved with a national aftermarket converter policy that made use of the same higher performance OBD-compliant aftermarket converters available in California and the states that adopted their requirements. For example, CARB estimated that requiring these advanced aftermarket converters in California would result in the reduction of over 36 tons/day of HC + NOx, at a cost effectiveness of $3,760/ton in 2012, once the new technology was fully implemented. Similarly, the Ozone Transport Commission estimated a reduction of 12,000 tons/year of NOx and HC (36 tpd) from the in-use light-duty fleet in the Northeast and Mid-Atlantic states through adoption of stricter aftermarket converter standards under a revised federal program.

MECA contracted with ENVIRON to run the MOVES2014 model and calculate the emission inventory reduction in tons per year of ozone precursors as a result of just upgrading the federal requirements to match the California 2009 standards. We believe this change could be fully implemented before 2025 because the technology is available and already being sold in California since 2009 and New York State since 2014. Based on state inspection and maintenance program statistics and MECA's annual aftermarket converter sales surveys, approximately 1% of light-duty vehicles experience an OBD catalyst error code, or fail their IM-240 emissions test, as a result of a damaged converter. We assumed a 2018 implementation date in our modeling work and a five year life for an aftermarket converter based on the duration of a California warranty. It was assumed that after 5 years the aftermarket converter would be replaced with another aftermarket converter resulting in full implementation of the advanced technology after five years. The maximum reduction benefit would be achieved over 5% of the total light-duty car and truck fleet. The MOVES2014 model predicts that 8,800 tons/year of NOx + HC would be reduced if an aftermarket converter policy were applied to those counties not in attainment with the 70 ppb NAAQS. If an aftermarket converter policy were applied to those counties not attaining a level of 60 ppb, 20,600 tons/year of NOx + HC would be reduced in 2025. Extended to the 47 contiguous states plus D.C. the reduction potential grows to 31,500 tons/year of ozone precursors. These NOx and HC reductions can be achieved by an average incremental cost of only $150 above the cost of today's federal aftermarket converter.

In reality the NOx emissions impact could be much worse now that most states are relying on OBD-based inspection and maintenance programs. When a typical EPA certified Tier 2 Bin 5 vehicle triggers an engine light (MIL) it could be emitting only slightly above its certified emission limit. By replacing the deteriorated OEM converter with a brand new EPA aftermarket converter, that is required to achieve only a 30% reduction in NOx, the vehicle may end up emitting far more NOx, as much as 14 times more, than it was emitting before the deteriorated OE converter was just replaced. On the other hand, a new California aftermarket converter must match the emission limit that the vehicle met when new and is equivalent to the OEM converter.

Another strategy that can achieve additional NOx emission reduction to meet the most stringent ozone standards would be for EPA to adopt California's 0.6 g/bhp-hr HC + NOx, 2010 emission standard for off-road spark-ignited engines with power ratings greater than 25 horsepower. The technology to reduce emissions from these SI engines is based on automotive-type closed-loop, three-way catalyst technology. This technology has been used on hundreds of millions of automobiles with outstanding results. These same catalyst technologies have been adapted to spark-ignited engines used in off-road mobile sources such as forklift trucks, airport ground support equipment, and portable generators. Closed-loop, three-way catalyst-based systems are already being used on these large, spark-ignited, off-road engines to meet CARB's and EPA's 2004 3.0 g/bhp-hr HC + NOx standard. Closed-loop, three-way catalyst systems are also the primary technology pathway for meeting the EPA and CARB 2007 exhaust emission standard of 2.0 g/bhp-hr HC + NOx. Retrofit kits that include air/fuel control systems along with three-way catalysts have been sold into the LPG-fueled fork lift industry for installation on uncontrolled engines (an LSI application) for nearly 10 years. In both new engine and retrofit applications, these closed-loop three-way catalyst systems have shown durable performance in LSI applications, consistent with the excellent durability record of closed-loop three-way catalyst systems used in automotive applications for more than thirty-five years. MECA believes that advanced three-way catalyst technology based on automotive applications can provide a cost-effective, durable, high performance solution for controlling NOx and HC emissions from new and existing large spark-ignited engines used in mobile and stationary applications.

MECA believes that additional NOx emissions reduction can be achieved by adopting more stringent HC + NOx emission standards for Class II off-road, spark-ignited engines with horsepower ratings less than 25 horsepower. Further reductions of HC + NOx emissions than what is required by the current Phase III EPA standards for these nonroad gasoline engines is technologically feasible through the use of catalyst technology that is fully optimized as part of a complete engine/emission control/exhaust system. Small engine manufacturers have been able to meet these standards through the redesign of existing Class II engines or through the use of emission credits, without the application of three-way catalysts. CARB is currently undergoing a rulemaking to adopt more stringent emission standards (by as much as 90% lower) for these classes of engines. Both EPA and CARB have shown that the application of catalysts to nonroad equipment with Class II spark-ignited engines can be accomplished using available engineering exhaust system design principles in a manner that does not increase the safety risk relative to today's uncontrolled equipment. In particular, the EPA safety study on non-handheld equipment outfitted with catalyzed mufflers represents the most thorough safety study completed to date on this class of spark-ignited engines. The results of this EPA study showed that properly designed catalyzed mufflers pose no incremental increase in safety risk (and in many cases even lower muffler surface temperatures) relative to currently available non-handheld equipment sold without catalysts. An opportunity for further reductions in Class II HC + NOx emissions through the application of three-way catalysts should be considered by EPA as a way to achieve reductions of ozone precursors from this sector of engines. Furthermore, small engines pose significant health exposure hazards to end users due to the close proximity to the exhaust during normal operation. These health exposures to toxics and criteria pollutants should be considered as part of future justification to further tighten emission standards for small spark-ignited engines.

Other off-road spark-ignited engines including those used on ATVs, off-road motorcycles, outboard marine engines, and snowmobiles are contributors to mobile-source hydrocarbon and NOx emissions. MECA believes that hydrocarbon and NOx emissions from these recreational engines can be significantly reduced by adopting tighter regulations that employ the use of advanced three-way catalysts for these mobile sources. All classes of off-road, spark-ignited engines can also benefit from advanced materials and systems developed for controlling evaporative emissions from PZEV or SULEV light-duty, gasoline vehicles. Recognizing the significant source of VOC emissions from recreational spark ignited engines, California has tightened evaporative emission requirements for several classes of off-road gasoline engines. For example, more stringent marine evaporative emission standards for larger engines were introduced in 2018 and include new fuel hose, tank, venting, and fuel injection requirements. More stringent fuel hose permeation limits started in 2020. In 2013, CARB adopted more stringent evaporative standards for recreational motorcycles that require low permeability tanks and hoses, as well as carbon canisters to achieve the new 1 g/day total organic gas emission limit. In 2019, CARB adopted a regulation that will phase out the state's allowance of "red sticker" recreational motorcycles, which were granted exemption from exhaust and evaporative emission standards if use was restricted to certain areas and seasons. EPA should review their evaporative emission requirements for all classes of off-road, gasoline engines and revise them to ensure that best available evaporative emission technologies are used in these applications.

On-road motorcycles are relying on three-way catalysts in the U.S. to comply with CARB's 2008 and EPA's 2010 exhaust emission standards. However, the exhaust and evaporative emissions of these catalyst-equipped on-road motorcycles will still be at levels considerably higher than late model, light-duty gasoline cars and trucks. Additional HC + NOx reductions can be obtained from on-road motorcycles through the use of engine, exhaust, and evaporative emission control strategies employed on today's best-in-class light-duty gasoline vehicles. The European Union's Euro 5 standards for two and three-wheeled vehicles went into effect this year, and these standards include a much tighter NOx emissions limit (60 mg/km) as well as PM emissions limit (4.5 mg/km), bringing motorcycle emissions limits on par with modern passenger cars. Several other countries, including Brazil, China, Japan, South Korea, Chile, Indonesia, and India, have plans to implement the Euro 5 motorcycle standards in the near future. CARB is currently considering a rulemaking to harmonize with many aspects of the Euro 5 standards, including tighter evaporative emission requirements. It is important that EPA also consider the adoption of more stringent motorcycle emission standards that are already being met in other parts of the world.

Direct Ozone Reduction Catalysts

All of the previously described technologies reduce the precursors to ozone formation. Direct ozone reduction systems consist of a special catalytic coating placed on a vehicle's radiator (or other surfaces such as the air conditioning condenser) that promotes ozone-reduction reactions in the ambient air. As the air passes across the warmed coated surfaces during normal driving, ambient ozone is converted into oxygen. CARB and EPA adopted a policy which allows manufacturers to offset higher tailpipe emissions by equipping vehicles with direct ozone reduction systems. Under this policy, vehicle manufacturers may receive emission credits for direct ozone reduction systems.

Conclusion

In closing, we believe that there are proven and cost effective gasoline and diesel engine emission control technologies available for achieving significant reductions in HC and NOx emissions from new and existing on-road and non-road engines, vehicles and equipment. These technologies have evolved significantly in their emission performance and are able to meet even tighter emission standards than are in place today. Once appropriate health-based standards are in place, our industry is prepared to work with EPA to review existing standards and tighten them where appropriate and cost effective to help states achieve the most stringent ambient ozone standards under discussion by EPA experts and others.

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