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

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

May 16, 2022

The Manufacturers of Emission Controls Association (MECA) is pleased to provide comments in strong support of the U.S. EPA's notice of proposed rulemaking (NPRM) to revise oxides of nitrogen (NOx) emission standards for heavy-duty on-highway engines as well as update greenhouse gas (GHG) emission standards for heavy-duty on-highway vehicles. We believe an important opportunity exists to continue to reduce NOx and GHG emissions from heavy-duty engines and vehicles due to the evolution of engine and aftertreatment technologies in the 12 years since the last standards were fully implemented. In addition, we support continued reductions in GHG emissions from medium- and heavy-duty engines and vehicles through the application of innovative technologies and fuels.

MECA is a non-profit association of the world's leading manufacturers of technology for clean mobility. Our members have over 45 years of experience and a proven track record in developing and manufacturing emission control, engine efficiency and electric propulsion technology for a wide variety of on-road and off-road vehicles and equipment in all world markets. 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 electrification, 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, emission reduction 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.

Finalization of the proposed regulatory provisions will provide certainty to suppliers and their OEM customers. Suppliers have been making investments in research and manufacturing to prepare for the future needs of their customers. MECA appreciates all of the time and effort that EPA staff put into the regulatory process for this important regulation, including coordinating with CARB staff as they developed and finalized their Low-NOx Omnibus Regulation last year. We thank EPA staff for their dedication in receiving and incorporating feedback from a broad range of stakeholders.

SUMMARY

MECA thanks EPA for building upon the historic comprehensive test program that has demonstrated pathways for heavy-duty engines to achieve ultra-low NOx levels without impacting GHG emissions and provided data on end-of-life durability, performance over real-world cycles, in-use system compliance with the new moving average window requirements, emission sensor measurement capability, among others. MECA supports EPA's Proposed Option 1 with some modifications, which we feel will strengthen the regulation. We also support EPA's amendments of the Phase 2 MY 2027 GHG vehicle standards and have some suggestions on how the NPRM treats credits from electric vehicles. Our suggestions for EPA's consideration are summarized here and explained in greater detail in the text that follows:

1. EPA should set an intermediate life standard for MY 2027.
2. EPA should consider a tighter LLC limit for MY 2027 and MY 2031 phases of Proposed Option 1.
3. EPA should consider both tightening the idling limit as well as making it a certification requirement.
4. EPA should consider tighter in-use compliance standards commensurate with the recommended LLC and idling standards in number 2 and 3 above.
5. EPA should reduce the MY 2027 FEL cap to 0.05 g/bhp-hr.
6. ZEVs should continue to be excluded from earning NOx credits.
7. ZEV GHG credit multipliers should be phased out faster than the proposed schedule in the NPRM and possibly before MY 2027.
8. We encourage EPA to work with CARB to explore a collaborative demonstration program that could be undertaken in the years leading up to implementation of the new requirements and designed to work with truck fleets to survey field aged parts on in-use trucks to examine real-world deterioration from a representative cross-section of vehicle age, state of repair and ownership status.

BACKGROUND

Emissions Inventory and Air Quality Analysis

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 Clean Trucks Rule to align with the CARB proposed limits and implementation dates [1] [2]. 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 Clean Trucks 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 Clean Trucks Regulation – 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 Clean Trucks Rule.

Results from the inventory analysis 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. 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. 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.

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 California Omnibus standards 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 that 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. Without a federal HD low NOx regulation, nearly 300 monitoring sites are projected to have 8-hour ozone design values between 60 and 70 ppb, and standards consistent with Proposed Option 1 will reduce these by an average of 2.35 ppb and up to a max of 5 ppb.

RECOMMENDATIONS

MECA Supports EPA's Proposed Option 1 NOx Stringency and Final Implementation Dates with Suggested Minor Changes.

Technology commercialization has a long cycle, including design, testing, vehicle integration and real-world deployment across many trucks in the field to make sure systems are reliable and durable. This cycle is why long-term regulatory certainty and stringent standards are a critical signal to industry to begin making investments and collaborating with their suppliers of technologies that will be needed in the future. MECA members have been 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 standards founded on technologically feasible and cost-effective solutions that allow communities to meet their air quality goals. In 2013, SwRI was granted a contract to demonstrate the technical feasibility for achieving a 90% reduction in NOx emissions below current standards while not negatively impacting CO_2, N_2O, methane, ammonia and other criteria pollutants including PM. This demonstration program has evolved and grown through EPA's support and continues to yield results to this day.

MECA supports EPA's proposed phased-in implementation dates beginning with MY 2027 and fully phased in by MY 2031, as these align with CARB's second phases of the Omnibus Regulation. The initial implementation starting with MY 2027 coincides with 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 emission reductions from engines and aftertreatment simultaneously. This alignment is the most cost-effective approach for engine manufacturers and suppliers as many technologies described below offer simultaneous and synergistic reductions in both NOx and CO_2.

One area of misalignment between EPA's Proposed Option 1 and CARB's Omnibus is the lack of an intermediate useful life standard for MY 2027-2030 engines in Proposed Option 1. MECA suggests that EPA add an intermediate standard for these model years that must be met for the first 435,000 miles of an engine's useful life. We believe that an intermediate standard will result in two major benefits compared to Proposed Option 1. First, it will lead to more robust emission control systems being installed on trucks and keep marginal systems off the roads. Second, this approach has precedence and better aligns with a single national program. In addition to the CARB and EPA engine and aftertreatment configurations being tested at SwRI, several other technologies and system configurations were also tested on technologies that were outside the scope of the agency work plans. Results from these parallel demonstration programs prove that there are further options to meeting the 0.02 g/bhp-hr standard at 435,000 miles. Three recent papers presented at the 2021 and 2022 SAE WCX meetings highlight the application of cylinder deactivation, supplemental heat and advanced aftertreatment to achieving down to 0.012 g/bhp-hr, which provides margin to the 0.02 g/bhp-hr proposed standard. The supplemental heat can be via a fuel burner [3] [4]or an electric heater [5]. A pre-publication paper that will be available later this year will summarize several engine and aftertreatment technology combinations along with calibration and dosing strategies that show great promise in achieving the Proposed Option 1 standards as well as an intermediate useful life standard of 0.02 g/bhp-hr at 435,000 miles.

MECA suggests that EPA consider tightening two categories of the Proposed Option 1 standards such that they are more stringent than those finalized in CARB's Omnibus. This recommendation is based on new, previously unavailable test results that have been released since the adoption of the Omnibus. Further testing on certification and real-world field cycles suggest that tighter standards are possible while retaining sufficient compliance margin that engine manufacturers need to account for manufacturing and field variability. We strongly encourage CARB to review this new test information and harmonize with EPA on more stringent standards. The two standards that can be tightened are the LLC standard and the idle standard. Similar to CARB's Omnibus, the idle standard should also be required for certification rather than an optional standard as currently proposed. There is significantly more data available from the SwRI demonstration program since CARB developed its Omnibus regulation. These data show that the LLC and idle standards finalized by CARB and proposed by EPA in Proposed Option 1 can be achieved with significant margin. The NOx level achieved over the LLC with systems fully aged to 800,000 equivalent miles is 0.037 g/bhp-hr, which includes the infrequent regeneration adjustment factor (IRAF) [6].

MECA recommends that EPA tighten the in-use compliance standards and moving average bin limits commensurate with a lower LLC certification standard. In the SwRI demonstration program, the 800,000 mile aged parts were also tested over several field duty cycles and results calculated with the new three bin moving average window (3B-MAW) in-use compliance methodology. The results for the low load bin (Bin 2) ranged from 0.033 to 0.048 g/bhp-hr, which provides 70% or more margin to the standard (0.15 g/bhp-hr). The results for the idle bin (Bin 1) ranged from 0.4 to 3.3 g/hr, which provides 60% or more margin to the optional standard (7.5 g/hr). Tightening the standards in line with test data and compliance margin would prevent emission backsliding over the life of the engine and ensure emissions are maintained as low as possible in underserved communities where low speed operation and idling operations are most likely to occur.

In addition, MECA supports EPA's proposed PM standard of 0.005 g/bhp-hr on the FTP and RMC cycles for MY 2027 and later engines. This PM standard is technologically feasible with currently available DPF technology as supported by the certification data of current heavy-duty diesel engines that implement DPFs, which report substantially lower PM measurements. This more stringent standard will prevent backsliding by ensuring the best available DPFs remain an integral component in aftertreatment systems. In response to tighter PM limits signaled by the EU and CARB's Omnibus, DPF suppliers are delivering improved filter substrates that have smaller mean pore size and more uniform pore size distribution, resulting in higher filtration efficiency and reduced pressure drop as the filter loads with soot. These improvements result in reduced particle number and mass emissions by up to 50%, even on a clean or freshly regenerated filter, better light-off performance necessary for soot regeneration and potential fuel economy benefits [7].

A robust test program was conducted to demonstrate that technologies can achieve the proposed standards.

The proposed emission limits have been derived from years of technology demonstration and testing at Southwest Research Institute under CARB and EPA contracts that began in 2014 and have 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 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 turbo-compounding 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 [8] [9] [10].

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 turbo-compound unit at low loads required active thermal management at a fuel penalty of about 2%, we did learn 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 and employed a different state-of-the-art 15L engine that met the 2017 Phase 2 GHG limits without the use of turbo-compounding. 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 build additional compliance margin against 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.

It should also be noted that technology demonstration on a vehicle has been conducted to support the European Union ongoing process of considering more stringent heavy-duty criteria emission standards in a Euro VII rulemaking. This work, conducted by the Association for Emission Controls by Catalyst (AECC) is showing that stringent NOx emission limits can be met on a vehicle in real world driving conditions by employing similar technologies demonstrated in the program at SwRI [11]. The integration onto an existing truck chassis required a slightly modified close-coupled catalyst architecture and demonstrates yet another pathway to achieving low NOx emissions. Further work by AECC demonstrated that integrating an electrically heated catalyst (EHC) with the close-coupled DOC yielded an additional 60-77% reduced NOx during cold start in an urban delivery drive cycle [12].

Technology development and optimization have continued, resulting in a large set of cost-effective technology solutions.

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 8 years of testing under this program. Further improvements in catalysts and architectures have been tested in the latest EPA-led portion of the test program that built on the learnings of the CARB funded portion of the program.

Catalyst suppliers have already developed a next generation of SCR catalysts with higher NOx reduction efficiency and better durability compared to the Stage 3 parts tested in the SwRI demonstration program. Through the use of sophisticated models that incorporate the latest learnings on both thermal and chemical aging effects, it is possible to project the gains in efficiency provided by these new materials. A similar methodology was used to that discussed in the MECA 2027 white paper, incorporating exhaust information from the latest engine calibration from SwRI and an optimized dosing calibration for the new downstream SCR catalyst. The catalysts were laboratory aged both thermally and chemically using sulfur containing simulated exhaust gas to represent 435,000 miles of equivalent engine aging. The catalysts were modeled over the FTP, RMC and LLC certification cycles and demonstrated lower emissions than the Stage 3 system at SwRI. The not yet published results suggest that the latest generation SCR catalyst would provide OEMs with additional margin to a 0.02 g/bhp-hr standard.

Furthermore, even in the short time since the latest emission control system was provided to SwRI for the demonstration program, improvements continue to be made to substrates and catalysts. For example, a recent paper published at the 2022 SAE WCX conference describes development of high-porosity honeycomb substrates with thinner wall thickness and high cell density that can be coated with SCR catalyst. The combination of developments on this substrate enables higher surface area and lower thermal mass, which improves coating efficiency, reduces catalyst heat-up time, and reduces pressure drop. These result in performance improvements that are especially prominent at low temperature operation. At engine exhaust temperatures of 175°C, the NOx conversion efficiency improved by 14% compared to earlier generation substrates [13].

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 15 years of advanced emission controls on trucks. In fact, over the life of the SwRI program, catalyst suppliers have deployed new catalyst formulations and coating techniques to continually improve the durability and performance of the SCR system in order to build greater compliance margin relative to the program targets. Our industry has seen a tremendous amount of innovation on both engines and aftertreatment since the U.S. 2010 on-road diesel standards were implemented. This learning has been applied to improve manufacturing and reduce variability that has allowed systems to be downsized by about 60% and reducing their costs by about 30% (costs will be further addressed later).

In addition to on engine and aftertreatment technology innovation over the course of the demonstration program, a new engine architecture has been developed and tested. The engine has been commercialized by Achates Power and is a 400 hp, 10.6L opposed-piston configuration. Besides being tested on an engine dynamometer, the engine has been installed in a Peterbilt 579 tractor that is current in fleet service with Walmart. The results from the test program show that the opposed piston engine combined with current commercially available aftertreatment systems can achieve NOx emissions of 0.007 g/bhp-hr on the FTP cycle, 0.014 g/bhp-hr on the SET, 0.02 g/hr on the clean idle cycle and 0.021 g/bhp-hr on the LLC after 435,000 equivalent aging. These values offer substantial margin (30-65%) relative to the 2031 limit ofthe Proposed Option 1 standards with greater than 50% margin under all operating modes [14].

Another promising technology that is being explored to both reduce the NOx and GHG footprint of heavy-duty vehicles is the hydrogen internal combustion engine (H2ICE). These engines, when coupled with advanced NOx aftertreatment, have the potential to meet the proposed NOx limits while emitting zero tailpipe carbon emissions when operated on any hydrogen fuel and zero lifecycle carbon emissions when operated on renewable green hydrogen. There is broad industry support for internal combustion engines fueled with clean hydrogen, including most engine manufacturers and component suppliers conducting significant development work and on-road demonstration in trucks. H2ICE are attractive options in commercial trucking where challenges exist in applying current BEV technology, with one of the main benefits being the opportunity to leverage existing investments in manufacturing capacity in engines and aftertreatment while growing the market for on-board hydrogen storage technology and infrastructure.

H2ICE vehicles share many components with today's diesel and natural gas powered vehicle fleet, including the base engine, installation parts, powertrain components and aftertreatment system architectures. Furthermore, H2ICE can borrow technology from currently available natural gas engines, such as cylinder heads, ignition systems, fuel injection, turbochargers, cooled exhaust gas recirculation (EGR), and engine control unit/software, among others. Nearly all on-road and off-road engine OEMs, along with their suppliers, are developing H2ICE for commercial introduction in the MY 2025-2027 time frame.

This regulation will complement CARB's Omnibus to set the goals for engineers at OEMs and suppliers who will work together to make these systems more robust and durable as they are integrated on trucks and tested in the field. This collaboration is only possible once new standards are set and our industry is motivated to work with our OEM customers to meet them. As part of this process, over the next several years, a number of observations from the SwRI program will be evaluated and applied to make further improvements to the engine-out and tailpipe NOx limits. This partnership between suppliers and their customers will lead to improvements in durability while delivering the compliance margins that OEMs rely upon when certifying engines and emission control systems. Some of the areas for improvement that have been identified include:

1) Applying improved substrates and catalyst formulations that target poisoning resistance at low temperatures while retaining high temperature ammonia selectivity.
2) Adjustments in catalyst volume and engine calibration to accommodate catalyst aging for longer useful life.
3) Packaging improvements for passive thermal management and ammonia mixing and distribution for optimal urea utilization.
4) Modified catalyst component architectures that take advantage of passive thermal management, NO oxidation capability and further reduced fuel consumption.
5) Close attention to engine and urea dosing calibration over all duty-cycles to ensure optimal ammonia surface coverage of the upstream and downstream SCR to optimize catalyst utilization.
6) Improvements in NOx and ammonia sensor accuracy and detection.

Over the past 12 years of diesel aftertreatment experience, our industry has learned a great deal about the design and operation of advanced diesel aftertreatment systems based on a DOC, DPF and SCR and the use of liquid urea to reduce NOx. The next 5 years will build on that learning to essentially use the same fundamental components to achieve a further 90% reduction in NOx. Passenger cars have had the benefit of 45 years of engine and aftertreatment development to achieve SULEV emissions. The SwRI program has demonstrated that near SULEV emissions are also achievable from heavy-duty engines to match the NOx emissions from natural gas engines that have operated at 0.02 g/bhp-hr levels for years. A more detailed discussion of the multiple technology pathways to achieving the emission limits proposed in this rule is provided below.

Commercially available technologies have been demonstrated to meet a 0.035 g/bhp-hr FTP NOx standard at 600,000 miles full useful life by 2027. These technologies can also enable a 0.02 g/bhp-hr intermediate FTP NOx standard at 435,000 miles.

Engine technologies, advancements in engine calibration, thermal management, and catalysts can be combined to enable engines plus aftertreatment systems to achieve FTP and RMC emissions below 0.02 g/bhp-hr NOx [15]. Ongoing work by MECA members is aimed at demonstrating emission levels that will provide sufficient compliance margins that OEMs need for full useful life durability. Recent testing funded by EPA further optimized the engine and aftertreatment system based on lessons learned during Stage 3 of the CARB Low-NOx Demonstration Project. During cold-start and low-load operation, which are challenging conditions for emission control, engine technologies can be combined with calibration and thermal management to reduce engine-out NOx emissions and achieve real-world NOx reductions. Engine calibration and thermal management combined with advanced catalysts and substrates have improved to the point where a current technology engine plus aftertreatment system can achieve FTP emissions below 0.05 g/bhp-hr NOx by 2024 to meet the CARB stage 1 standards.

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 0.02 g/bhp-hr after 435,000 miles by 2027. Several potential future aftertreatment layouts have been demonstrated in the SwRI test program. MECA has published two white papers that outline the technologies and models used to design catalyst, substrate and architectures to meet ultra-low NOx levels [16] [15]. Over the past 8 years of demonstration work at SwRI, testing has confirmed MECA's modeled results while also showing the need for modest enhancement of emissions control durability to provide margin for the FTP and RMC cycles over extended useful life. Over the next five years, industry will embrace any remaining challenges as suppliers continue to optimize their components and engine manufacturers hone their calibrations to exceed what has been demonstrated to date. This continued improvement work is why MECA believes that an intermediate limit of 0.02 g/bhp-hr is a technologically achievable up to 435,000 miles for a national program by 2027.

EPA has used intermediate standards previously in the Tier 2 passenger car regulation to keep marginally designed emission control systems out of the market so only the most robust designs remain on the roads for their useful life. This is particularly important in trucks that can last 20 to 30 years with multiple owners and duty cycles.

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

The penetration of fuel-saving technologies into the heavy-duty fleet has been spurred by U.S. EPA's Heavy-Duty Greenhouse Gas Phase 1 and Phase 2 Standards. 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 have been demonstrating even greater gains in fuel and freight efficiency, with engines achieving 55% brake thermal efficiency through the use of technologies like waste heat recovery. Last year DOE awarded five OEMs funding to develop electric powertrains in SuperTruck III.

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 – 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.

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 technologies to reduce tailpipe NOx from diesel engines have 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, U.S. 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 1). 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. Setting stringent emission targets for both CO_2 and NOx through realistic regulations has caused engine calibrators to expand their toolbox from the engine to the powertrain to enable simultaneous NOx reductions and engine efficiency improvements.

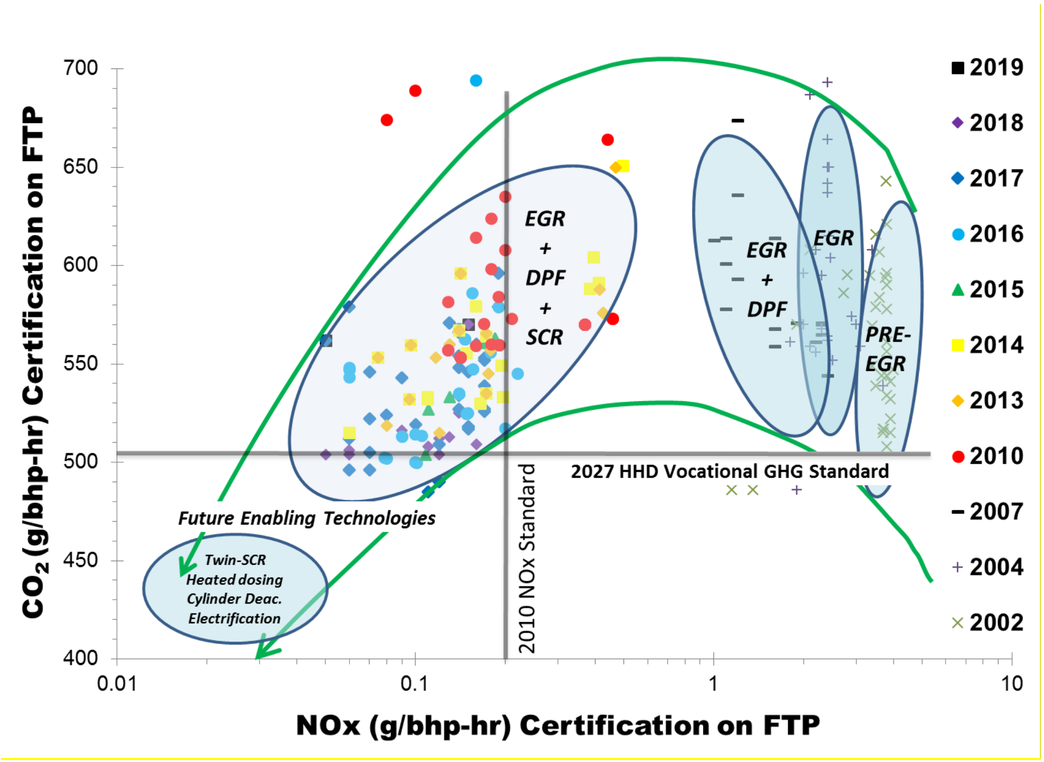

Figure 1. Model Year 2002-2019 Heavy-Duty Engine Certification Test Data for NOx and CO_2.

<u>Advances in thermal management, air handling and electrification technologies enable high catalyst performance required to reduce NOx to meet the proposed emission standards.</u>

Thermal management of the SCR system is critical to achieving low NOx emissions during low load operation. Traditionally, under colder exhaust operating conditions, engines would be calibrated to run hotter via higher idle speeds, late fuel injection into cylinders or by injecting fuel 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 passive 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. All 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.

At low load, a bypass alone may not yield enough heat using standard diesel engine combustion techniques. Several advanced thermal management strategies will provide options for engine manufacturers to calibrate engines to simultaneously heat up exhaust and save fuel, which can offset the costs of the technologies to their customers. Technologies such as fuel burners and electric heaters in combination with cylinder deactivation and advanced aftertreatment systems have been demonstrated to achieve ultra-low NOx levels without increasing CO_2 emissions [3] [4] [5]. The reason for this is due to their efficiency in generating heat compared to traditional methods of late post-injection of fuel across a DOC. In fact, these technologies have been tested across several drive cycles in conjunction with the systems in the SwRI demonstration program. Results for the FTP show the ability to meet 0.012 g/bhp-hr with a 1.6% reduction in CO_2. Depending on the actual calibration and control of the heat source, the system can be optimized to reduce both NOx and CO_2 or favor one of these for greater reductions while holding the other neutral.

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 [15].

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.

Modern turbocharger

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 turbocharger 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 [17]. 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.

Turbo-compounding

Turbo-compounding 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 turbo-compounding has been employed on some commercial diesel engines, and EPA estimated penetration to reach 10% in the U.S. by the time the Phase 2 GHG Regulation is fully implemented in 2027 [18]. An early 2014 version of a turbo-compound-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 [10, 8, 9]. While turbo-compounding 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 turbo-compound designs that incorporate bypass systems during cold start and low load operation or electrically driven turbo-compounding systems where the unit can be placed after the aftertreatment system.

Driven turbochargers

Driven turbochargers can be used to control the speed of the turbomachinery independently of the engine's exhaust flow and vary the relative ratio between engine speed and turbo speed. Driven turbochargers may be utilized for several reasons, including performance, efficiency, and emissions. Considered an 'on-demand' air device, a driven turbocharger also receives transient power from its turbine. During transient operation, a driven turbocharger 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 turbocharger 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 turbocharger perform all the functions of a supercharger, turbocharger, and turbo-compounder. NOx emission control uniquely benefits from the application of driven turbochargers 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 [19]. 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 [15].

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 48-volt 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 employed 48-volt technologies on their vehicles to demonstrate trucks with greater than 55% brake thermal efficiency. A recent study demonstrated through model-based simulations that a 48-volt technology package combined with advanced aftertreatment can achieve a composite FTP emission level of 0.015 g/bhp-hr [20].

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 [15].

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 [21]. 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 [15].

As noted above, the types of technologies that enable electrified heavy-duty vehicles are already commercially available with more anticipated by 2027. MECA supports EPA's proposal to revise the Phase 2 vehicle GHG limits for MY 2027 based on EPA's analysis in this rule of the projected penetration of heavy-duty electric vehicles. Some barriers that remain, such as infrastructure needs, should be addressed through state and national efforts. MECA supports EPA revisiting projections of heavy-duty electric vehicle penetration, as challenges to electrification of the heavy-duty sector are overcome.

MECA supports the inclusion of a low load cycle and standard to certification requirements that achieve low NOx emissions during low load operation.

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.

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 [22]. Results from this report provide some insights into the causes for NOx emission reduction challenges due to real world operation.

Some observations from this work are shown in Figure 4 and 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.

MECA supports EPA adopting, similar to CARB's Omnibus, revised regulatory requirements that aim to best control emissions at times of low load engine operation. During certification, the engines and aftertreatment systems would need to meet low emissions over the newly proposed low-load certification (LLC) cycle that targets average engine power of about 7%. MECA supports the addition of the LLC cycle in 2027 for engine certification. However, as stated in our comments on page 3-4 above, we believe the LLC standards at full useful life should be tightened for both MY 2027 and 2031. Testing at SwRI has shown that the Proposed Option 1 LLC standards can be achieved with significant margin at the proposed limits and may result in emissions backsliding over time in these operating modes that are the most critical to urban operation.

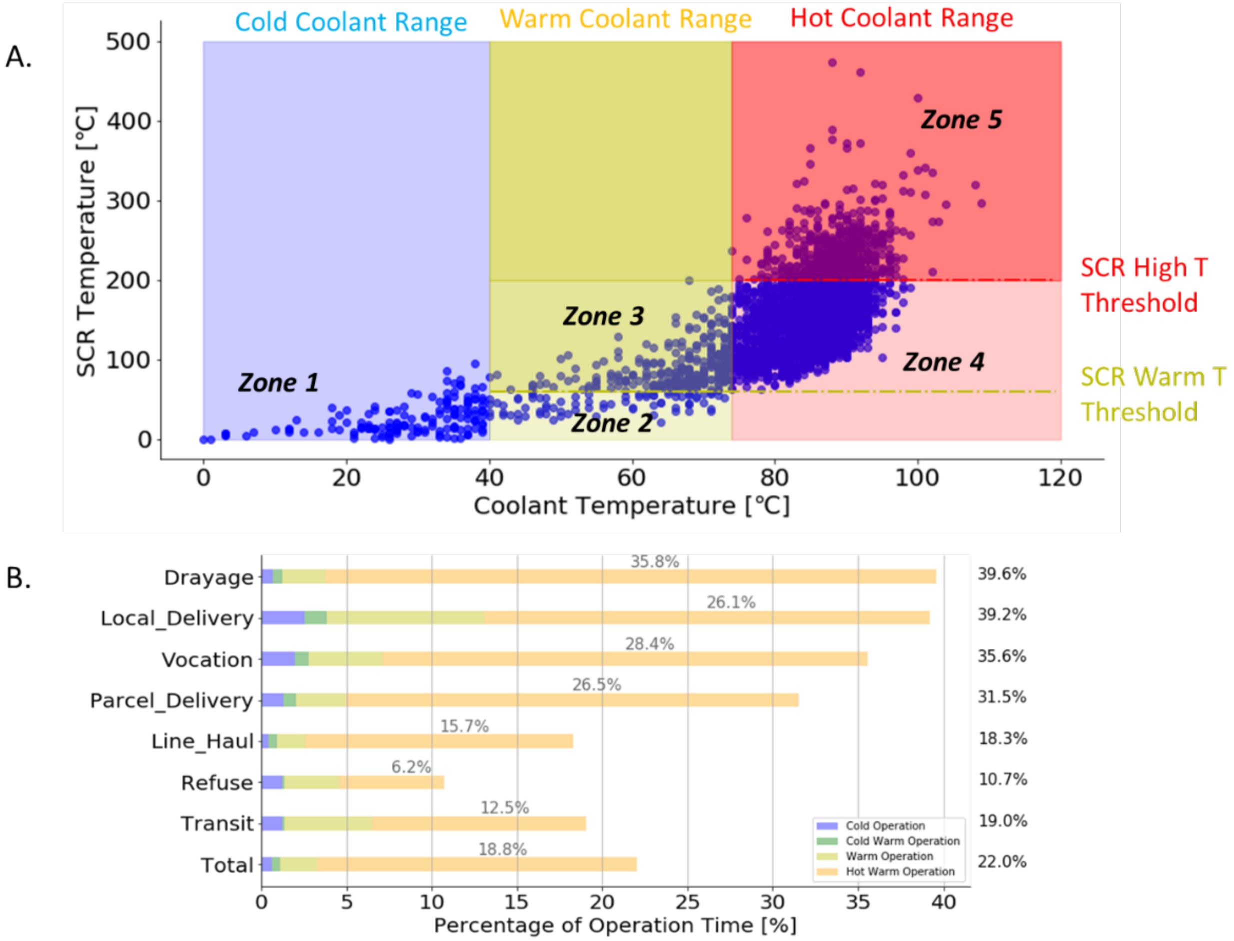

Figure 1. A) Number and type of engine start based on coolant temperature and SCR temperature. B) Percentage of time spent at different coolant-exhaust temperature conditions. Note: Engine starts defined as "cold" when coolant temp ≤ 40℃, warm-cold when coolant temp is between 40-75℃ and SCR temp is

≤ 60℃, warm when coolant temp is between 40-75℃ and SCR temp is between 60-200℃, hot-warm when coolant temp is > 75℃ and SCR temp is ≤ 200℃, and hot when coolant temp is > 75℃ and SCR temp is > 200℃.

Inclusion of the LLC is a very important part of this rule as it ensures that during certification, dynamometer testing evaluates the ability of technology to meet real-world emissions in an accurate test cell environment before they are deployed on the road. As discussed above, the cycle was derived from real truck data operated over actual duty cycles from many different truck vocations ranging from delivery to busses to line-haul tractors. The proposed LLC cycle is a robust approximation of all types of truck operation at low load. The approach used by NREL and SwRI to develop a real-world cycle stands as an example of how future certification cycles can be developed. MECA supports the inclusion of the proposed LLC cycle to give EPA the confidence, at time of certification, that the technology will be able to meet the requirements of the revised in-use compliance program proposed by staff based on a moving average window analysis. MECA members have developed and are offering a number of technology solutions (discussed previously) that can enable OEMs to meet the tighter-than-proposed LLC limits. Testing of the Stage 3 engine and aftertreatment systems have exceeded the proposed LLC emission limits with significant margin based on the same technology solutions that achieved ultra-low NOx emissions over the FTP, including over 98% conversion efficiency over the cold-start phase of the FTP.

MECA supports the proposed changes to in-use requirements that achieve low NOx emissions in the real world. However, it is feasible to tighten the in-use compliance limits for Bin 1 and Bin 2 operation.

The proposed rule sunsets the NTE program and replaces it with a moving-average-windows (MAW) type of emissions analysis based on similar methodology to the in-service conformity (ISC) requirements used in Europe. ICCT has shown that in Europe, where a MAW analysis has been required during ISC testing since 2013, the same type of aftertreatment systems used on Euro VI compliant trucks achieve much lower emissions than U.S. 2010 technology trucks at the low speeds often experienced in the real world [23]. CARB's in-use testing has confirmed the limitations of the current compliance program based on the Not to Exceed (NTE) requirements for trucks that currently certify to the FTP standard of 0.2 g/bhp-hr. Over real duty-cycles and the many exclusions allowed by the NTE program the trucks must meet a 0.3 g/bhp-hr on the road. CARB has shown and the ICCT has confirmed (in the report above) that only about 5% of the tests meet the conditions of a valid NTE.

When the NTE was first adopted as part of the U.S. compliance program, there were no aftertreatment systems on trucks and the program was effective at ensuring that engine calibrations were not being modified at highway speeds. However, after 2010 when SCR systems were installed, CARB and EPA began to observe that because the SCR catalyst operates at reduced efficiency below exhaust temperatures of about 200°C, in-use trucks are emitting multiple times higher NOx emissions than the FTP certification limit, resulting in high NOx emissions in urban areas, communities and ports where truck speed is low. The proposed three bin approach with 30 second windows is a better methodology than a power-based window approach or CO_2 equivalent based approach since it more evenly weights different engine operating modes, including extended idle and low power periods of operation.

SwRI engineers have tested the Stage 3 aftertreatment system, that was engine-aged to an equivalent of 800,000 miles, on a dynamometer over a speed-load trace from several actual drive cycles. These driving cycles include the Southern NTE route, drayage cycle, grocery cycle and a European in-use compliance drive cycle. The Southern NTE has been used by CARB for Heavy-Duty In-Use Testing and lasts approximately three hours and includes several challenging profiles, such as coasting, motoring and high transient return to service that requires the aftertreatment to stay hot as it prepares for acceleration under load. The CDA system on the engine retained heat in the aftertreatment by shutting down valves and cylinders during these coasting events and prevented cold air from being pumped by the engine into the aftertreatment system, thus keeping the SCR hot for the next transient acceleration. Over these real-world cycles, the system achieved extremely low tailpipe NOx emission limits for each bin. The results for the mid-high load bin (Bin 3) ranged from 0.022 to 0.046 g/bhp-hr, which provides 25-50% margin to the proposed Bin 3 limit (0.06). The results for the low load bin (Bin 2) ranged from 0.033 to 0.048 g/bhp-hr, which provides 70% or more margin to the proposed Bin 2 limit (0.15 g/bhp-hr). The results for the idle bin (Bin 1) ranged from 0.4 to 3.3 g/hr, which provides 60% or more margin to the proposed Bin 1 limit (7.5 g/hr) [6]. These results confirm the tremendous efficacy of the Stage 3 system for reducing emissions across the range of real-world operating conditions, especially in areas where reductions are most needed such as in urban city centers.

Diesel trucks can meet stringent emission limits over the course of longer lifetimes (warranty and durability).

We understand EPA's need to ensure that heavy-duty vehicles are meeting emission standards while in operation, which requires that emission critical components are durable and repaired quickly if a malfunction occurs. Based on several stakeholder meetings between EPA, CARB, and industry, we believe that EPA's Proposed Option 1 warranty and durability provisions have struck a suitable balance between stringency and phase-in time to allow suppliers to work with their customers to fill current information gaps and complete additional R&D to ensure future trucks continue to be durable and meet emissions warranty requirements. The phase-in approach will allow component suppliers to better understand the economic impact of longer warranty periods on their business as well as time to design longer durability into components. MECA supports hourly limits for vocational vehicles that may operate for thousands of hours at low speed or idle prior to reaching the mileage or year warranty clock threshold. We support Proposed Option 1 slight increase to the emission standards at the final longer durability periods to account for possible deterioration beyond the current FUL of 435,000 equivalent miles. Results from the SwRI demonstration program support the NOx limits at the FUL requirements in Proposed Option 1.

Finally, we encourage continued collaboration and discussion between EPA and CARB to study impacts of proposed warranty and durability requirements as the rule is implemented, given the lack of information on warranty and failure modes past today's FUL of 435,000 miles. Such efforts could be designed by working with truck fleets to survey field aged parts on in-use trucks to examine real-world deterioration from a representative cross-section of vehicle age, state of repair and ownership status. This would provide useful information to OEMs and suppliers working to meet Omnibus warranty and durability requirements and lead to emission controls with higher durability, lower warranty claims, and ultimately reduced emissions. A recent CARB-funded project where CE-CERT conducted testing to inform a future heavy-duty I/M program could serve as a model for a research program that identifies field aged parts in various conditions for retrieval and analysis.

As we previously commented, there is considerable uncertainty about the state of vehicles during the time of operation beyond today's 100,000 mile warranty. Much of the data on warranty claims and repairs as well as vehicle use characteristics originate from the time when the first owner operates a vehicle while data from repairs made by second and third owners is very limited. Many suppliers do not have data on the durability, replacement or diagnostics of their parts past the warranty because the dealer network is not required to share that information. This lack of information leads to challenges for suppliers who are trying to design parts that will meet the extended durability requirements out to 800,000 miles. Without warranty claim information beyond 100,000 miles, it is difficult for suppliers to estimate the cost impact of the proposed extended 2031 warranty and challenges suppliers trying to design to the much longer 2031 durability periods. The lack of data also challenges suppliers trying to design to longer durability periods. 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. Finally, besides the engineering design time needed to design components to longer durability requirements, the testing out to the long mileage durability requirements (such as 800,000 miles for class 8 engines), especially for on-engine components whose aging cannot be accelerated, takes months to years on dynamometers.

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. As noted above, wear of on-engine emission critical parts such as EGR, turbochargers, fuel injectors 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. Furthermore, there is 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.

MECA supports EPA's proposal 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).

EPA's regulatory framework offers the most comprehensive evaporative/refueling control program in the world for chassis certified vehicles. Onboard Refueling Vapor Recovery

(ORVR) has been successfully implemented in the U.S. and Canada for over 25 years. Within EPA's IUVP program, there have been over 4500 tests conducted on in-use vehicles equipped with ORVR with an average reduction efficiency of 98% [24]. The odometer readings on a large fraction of these vehicles exceeded 100,000 miles. 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.

Heavy-duty gasoline vehicles (HDGVs) fall into two categories. The first category, light HDGVs (LHDGVs) (GVWR < 14,000 lb.) are usually chassis certified and have been required to meet refueling emission standards since the 2018 model year. The second category, heavy HDGVs (HHDGVs) (> 14,000 lb. GVWR) usually are classified as incomplete vehicles since the engine is tested on a dynamometer for exhaust emissions and during production the engines are installed on a chassis where the chassis is completed by a secondary manufacturer [25] [26]. While Tier 3 evaporative requirements apply to HHDGVs, refueling emission standards do not yet apply to this subcategory of HDGVs. MECA estimates that HHDGV refueling emissions are equivalent to about 0.37 g/mile (based on 4.1 g/gallon emission rate and average fuel efficiency of 11 mpg). Control of refueling emissions with ORVR is a significant opportunity to reduce VOC emissions (ozone and PM2.5 precursors and air toxic emissions) from these HDGVs.

Specific to EPA's proposal, MECA supports extending ORVR requirements to HHDGVs at a refueling emission standard of 0.20 grams hydrocarbon per gallon of liquid fuel dispensed as now applies to LDVs, LDTs, MDPVs, LHDGVs, and complete HHDGVs. The OEMs have twenty-five model years of experience with the design and certification of ORVR systems, which together with the EPA IUVP data mentioned above, clearly demonstrate the feasibility. Very recently, a complete HHDGV with a fuel tank of one hundred gallons was certified to ORVR for the 2022 model year [27].

Consistent with the current requirements for evaporative emission and refueling emission controls for all lighter weight vehicles, MECA supports EPA's proposal to apply a useful life of 15 years/150,000 miles to the HHDGV refueling emission standard. The Tier 3 evaporative emission standard useful life for all HDGVs is currently 15 years/150,000 miles. Given that integrated ORVR/evaporative control system designs share hardware such as the activated carbon canister and purge valve and functions such as vapor transport and canister purge, a common requirement for evaporative and refueling emission standard useful life is logical and necessary.

MECA believes the implementation of ORVR is feasible and practical for primary and secondary manufacturers. Since the first HDGV evaporative emission standards were implemented in the 1985 model year, OEMs and secondary manufacturers now have thirty-five 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. In addition, there are now several regulatory provisions within 40 CFR §1037 which provide guidelines on how OEMs and secondary manufacturers may work together under EPA's certification programs [28]. This extensive experience together with these recent regulatory provisions suggest that any concerns have been addressed and there is no need for added regulatory measures. Regarding testing for refueling emissions certification, the ORVR test procedures promulgated in 1994 are fully fit for purpose and, perhaps with minor changes or clarifications, should be applied to HHDGVs using the driving cycles and SHED-test procedures currently specified in Subpart B. MECA supports a compliance demonstration through a full vehicle emission testing and certification as contained in Subpart B plus continuation of the manufacturers' certification option using the compliance demonstration flexibility provided in 40 CFR §1037.103(c).

Fuel Quality

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 a close-coupled dual-SCR aftertreatment architecture 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.

An aftertreatment architecture likely to be employed to meet the Proposed Option 1 standards may include a twin SCR arrangement with a close-coupled SCR that is upstream of today's aftertreatment systems. In the absence of an upstream DOC, 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. The SwRI Low-NOx Test Program has demonstrated that upstream SCRs in a dual SCR system can be brought up to temperature for desulfation via engine calibration to optimize short periods of higher temperature operation without incurring a fuel penalty or significant catalyst deterioration. The strategy employed by SwRI successfully removed sulfur from the SCR catalyst and reversed the marginal performance loss experienced due to sulfur deposition.

EPA has funded a continuation of the SwRI program with 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 are helping 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. Results of the aging demonstration conducted at SwRI have confirmed some loss of performance from 435,000 miles to 800,000 miles. However, the rate of performance loss was cycle specific. For example, the SwRI program results showed minimal loss of performance over the LLC (0.029 g/bhp-hr to 0.032 g/bhp-hr) from 435,000 miles to 800,000 miles for the latest system ("Stage3 RW") tested as of April 2022. The same deterioration over the FTP cycle test resulted in a 0.020 g/bhp-hr level at 435,000 miles compared to 0.037 g/bhp-hr at 800,000 miles. It should be noted that all of these results are under the Proposed Option 1 standards at 800,000 miles for MY 2031 engines.

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 [29]. More research is needed here to determine the durability requirements to meet future full useful life provisions; however, the results of the lube oil poisoning as accelerated in the SwRI program show good durability of the close-coupled SCR, which receives the bulk of the lube oil metal poisons. Possible future mitigation actions that catalyst suppliers can deploy 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 [30, 31]. 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 (NBB) 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 [32]. Similarly, in a later study, a heavy-duty 2010 style aftertreatment system architecture 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 [31].

The metal content of B100 from field samples analyzed by researchers at NREL [33] [34] [35] 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. MECA supports more stringent limits of fuel additives that contain metals including evaluating their potential impact on aftertreatment components. We have been working with NBB, OEMs and biodiesel producers to generate the necessary data that supports tighter ASTM specifications for metal impurities in biodiesel at or near the detection level of analytical techniques as a way to provide confidence to engine manufacturers that biodiesel fuels can be as clean as possible.

Current fuel quality in the market

CARB staff reported sulfur and metals levels in today's fuel supply for diesel engines without any applied corrections for volumes represented or market share of producers [36]. To better understand sulfur content and variability in the California fuel supply for diesel engines, CARB-collected over 400 fuel samples from California producers, importers and distribution terminals during 2017 to 2019 calendar years. These samples included diesel and some biodiesel and renewable diesel blends with maximum sulfur content observed of 13 ppm and an average sulfur content 4 ppm with a standard deviation of 3 ppm. These sulfur levels in current ULSD are adequate for engine and aftertreatment systems to meet the Proposed Option 1 standards.

CARB staff also collected and analyzed over 400 diesel and biodiesel blend samples collected at retail fuel pumps throughout California in 2019 [36]. The findings concluded that phosphorus and metal contents of biodiesel were significantly lower than current ASTM limits, which supports minimal impact of biodiesel metals and phosphorus on the full useful life durability of diesel exhaust aftertreatment systems. CARB staff also analyzed 27 B100 samples that EPA collected from biodiesel production facilities nationally and did not identify metals contamination. These results are consistent with trends seen in national biodiesel fuel surveys conducted by NREL and referenced above.

Costs to Meet the Proposed Standards

MECA agrees with EPA's cost analysis conducted to support this rulemaking. Similar to EPA, our estimates of the incremental technology costs to meet the Proposed Option 1 show that the technology packages on MY 2027 trucks would yield cost effective NOx reductions. In support of cost-benefit analyses funded by CARB and conducted by NREL as part of the development of the Omnibus, MECA estimated the costs (in 2019$) of the technologies employed in current trucks to meet today's emission standards as well as the technologies projected to be employed on trucks in future years to meet the requirements proposed in the Omnibus. In our cost analysis, we first estimated a cost range of current heavy-duty emission controls systems 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 direct hardware cost estimate for a current aftertreatment system on a vehicle with a 6-7L engine is about \$2,600 to \$3,500. This is similar to the costs estimated by the ICCT (\$2,807) in their most recent cost analysis [37]. For a Class 8 line-haul tractor with a 12-13L engine, we estimate a direct hardware cost of the engine and aftertreatment hardware to be in the range of \$3,500 to \$4,600 per truck. Similar to the 6-7L engine above, our cost is in-line with ICCT's latest estimate (\$4,365) [37]. An older 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 [38]. It is important to note that the average price of a heavy-duty line-haul truck has historically increased by about 1% per year [38] due to safety, operational and other customer demanded enhancements that truck manufacturers have made to trucks. At the same time, emission control technology suppliers are typically expected to reduce the costs of their components through manufacturing improvements and other optimization by about 2-3% per year [37]. The year-over-year supply chain reductions can account for much of the cost difference between recent cost estimates compared to those reported by ICCT in 2016. Given declining emission control system costs and increases in the average 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 an emission control system that includes a close-coupled SCR combined with a traditional aftertreatment system. 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 by SwRI. Two cost estimates were prepared – one that assumed today's durability and warranty requirements, and one assuming one 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. These durability and warranty levels were chosen because they were initially proposed by CARB during the Omnibus rulemaking [39]. Given EPA's Proposed Option 1 includes lower durability and warranty requirements than assumed in our cost analysis, 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, projected 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 increased 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 cost estimates are biased high since they are based on more stringent requirements than those included in Propose Option 1.

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 [40] following the 2017 Carl Moyer Guidelines [41], 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. EPA's estimate of $2,000 per ton NOx reduced for the 2010 heavy-duty NOx standards is within this range [42], 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 [43]. Similarly, CARB estimated the cost-effectiveness for future low-NOx requirements to be approximately $6,000 per ton [44].

The ICCT recently conducted an analysis that estimated the cost of diesel emissions control technology to meet CARB's Omnibus standards [37]. 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 [38]. In order to meet the proposed MY 2027 standards (similar to EPA Proposed Option 1), 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.

It should be noted that the cost estimates developed by NREL included the costs due to the extended warranty requirements, despite a lack of adequate information available from suppliers or OEMs to estimate these. Similarly, costs analyses conducted by ACT Research and Ricardo made assumptions for significant warranty costs due to the new regulation based on confidential surveys. NREL and CARB acknowledged that the cost estimates for extended warranty are very uncertain. CARB subsequently conducted its own analysis of costs needed to meet extended warranty requirements, and these are substantially lower than those estimated in the NREL report as well as those estimated by ACT Research and Ricardo. After the Omnibus was approved by its Board, CARB staff convened a working group of OEMs, EMA, and MECA to review warranty costs. This working group resulted in a final report in which CARB staff concluded that the methodology used to support the Omnibus Regulation warranty-related cost estimates is reasonable and defensible and they did not believe changes to those estimates were needed [45]. As stated above, this uncertainty in costs estimated to meet extended durability and warranty provides an opportunity for future collaborative work in the form of a study that includes fleets, industry stakeholders, CARB and EPA staff.

Regulatory Flexibility

MECA supports minor changes to the proposed ABT program to incentivize the cleanest trucks as early as possible.

MECA believes that incentivizing early introduction of technologies is an effective way of driving development of the cleanest technology ahead of regulations to deliver early emission reductions. We believe that staff's proposed use of NOx credit multipliers as phased-in by earliest year of introduction is appropriate and rewards manufacturers that have invested in the cleanest technology first with greater credits. Natural gas engines that are already emitting at the lowest 2027 limits will be able to generate these early compliance credits as investments are made to introduce diesel trucks that emit at these ultra-low NOx levels.

MECA is concerned with the credit mechanisms proposed for zero-emission trucks for both NOx and GHGs. First, we recommend a reduction in the FEL cap down to 0.05 g/bhp-hr at 435,000 miles that scales with FUL, which harmonizes with CARB's Omnibus. A higher FEL cap, such as the proposed 0.15 g/bhp-hr, would result in a loss in NOx emissions benefits that could disproportionately impact disadvantaged communities. Second, we support the exclusion of ZEVs from earning NOx credits. CARB originally proposed to allow ZEVs to earn NOx credits until MY 2030. However, after analyzing the impacts and considering the high anticipated uptake of electric vehicles over the next decade, CARB revised its proposal and will end ZEV NOx credits in MY 2026. MECA calculated that CARB's original proposal would lead to 12,000 higher emitting diesel trucks with service lifetimes of 10-15 years that could be sold in California alone, generating an additional 523 tons of NOx over their useful lives.

We believe that the NOx inventory impact from direct NOx credit averaging and banking is a conservative estimate because ZEV NOx credits fail to take into account the upstream NOx emissions from the electrical grid that will be used to charge electric trucks. Lifecycle emissions analysis is becoming the established methodology for understanding the upstream and downstream impacts of the transportation sector and can be used to predict the overall environmental impact of policy decisions.

To illustrate the relative NOx inventory contribution of battery electric trucks compared to their near-zero combustion counterparts, we relied on U.S. EPA's eGrid average annual NOx emission values for in-state electricity production. We took into account renewable energy targets (e.g., California has renewable energy targets of 44% in 2024 to 60% in 2030) and manufacturer claimed electric efficiencies from marketing materials. In our conservative approach, transmission and charging losses were not included, nor were smart charging strategies. Furthermore, fuel economy values of 7 mpg were approximated for Class 8 trucks using U.S. DOE and industry publications for diesel vehicles, even though these are lower than required by HD Phase 2 GHG regulations. Upstream fuel related NOx emissions from refining of 20% were also added.

On a gram-per-mile basis, a MY 2027 and later class 8 low NOx diesel truck will emit approximately 0.1 g/mile at full useful life. The grid emissions from the same weight class battery electric truck will lead to upstream emissions of 0.25 g/mile in 2024 and 0.18 g/mile in 2030 as the grid continues to incorporate higher percentages of renewable sources of energy. This analysis is not meant to suggest that one truck technology is cleaner than another since only NOx emissions were considered. It simply illustrates that crediting battery electric trucks as zero NOx in the ABT program is not warranted. Since EPA's Clean Trucks Rule starts in MY 2027, we encourage the agency to follow CARB and remove the ability for ZEV to generate NOx credits.

Heavy-Duty GHG Phase 2 Considerations

ZEV GHG credit multipliers should be phased out faster than the proposed schedule in the NPRM.

EPA is proposing to revise the HD Phase 2 GHG standards for MY 2027 vehicles in order to take into account the larger proportion of electric vehicles that are projected to be sold out to MY 2030. The original Phase 2 regulation did not take electric vehicle penetration into account when setting the standards, so many proponents of this revision cite the ability to meet lower GHG targets than originally proposed. MECA agrees with the change to vehicle standards proposed by EPA based on projected electric vehicle sales. For the same reason, we support EPA's decision to phase out GHG credit multipliers for battery electric vehicles. CARB's Advanced Clean Trucks (ACT) Regulation is expected to lead to significant penetration of electric and fuel cell vehicles in California as well as several Section 177 states.

The early introductory use of incentives can promote innovative technologies that can be disadvantaged by lack of customer exposure and experience. 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 while meeting performance based standards. Analyses by ICCT and researchers at Carnegie Mellon have shown that extended use of super credits in the light-duty sector has resulted in the unintended consequence of increased emissions from the non-ZEV fleet as it is allowed to emit more under a fleet average regulatory structure that includes averaging, banking and trading provisions [46] [47]. Given the current number of heavy-duty electric vehicle model offerings, declining costs of these vehicles and projected sales, large credits to OEMs are not needed to incentivize production. Similar to the light-duty sector, an over-incentivized credit scheme for heavy-duty ZEVs will instead result in erosion of ZEV sales and thus the benefits anticipated by the standards, especially when the upstream emissions from electricity generation are considered [48].

MECA supports two changes to ZEV advanced technology multiplier credits that will help to strengthen the proposal. First, EPA should eliminate advanced technology multiplier credits for ZEVs sold into California and all states that have adopted California's Advanced Clean Trucks Regulation, which requires year-over-year increasing sales requirements of advanced technology vehicles subject to the credits. Second, EPA should phase out the current advanced technology multiplier credits such that no multiplier exists as soon as practicable and no later than from MY 2027.

ADDITIONAL CONSIDERATIONS

Ensure that DPFs are being installed on Auxiliary Power Units (APU) that are implemented on HD trucks to reduce idle emissions.

EPA recognized the GHG reduction benefits of auxiliary power units (APUs) during the promulgation of the heavy-duty Phase II regulation. APUs utilize a small diesel engine to operate driver comfort systems rather than overnight idling of the main engine on Class 8 sleeper trucks. One APU manufacturer advertises savings of $428 per month when using a diesel fueled APU to supply auxiliary power compared to idling class 8 engine (2000 hr./yr. at $3/gallon fuel). Due to the quick return on investment from the fuel savings, APUs are quite popular with production volumes in the 25K to 40K units per year.

At the same time, EPA also understood that APU engine standards are less stringent than those for on-highway trucks. Permitting trucks with the latest engine and aftertreatment technology to employ APUs to reduce GHGs during idling would result in increased PM emissions unless DPFs were installed on the APUs. CARB has verified at least three diesel particulate filter models for APUs at the Level 3 designation (> 85% reduction) since 2008. These DPFs can be installed on Carrier, Proventia and Thermo King APUs, resulting in the production of more than 10,000 DPF equipped APUs for the California market. Therefore, EPA finalized stringent PM emission limits in the Phase II Heavy Duty GHG Rule for all Auxiliary Power Units (APUs) installed on new model year 2024 or later tractors. The agency noted that DPFs are viewed as the likely "emission control hardware" necessary to meet the standard.

MECA has learned that EPA has agreed with an interpretation of the Phase 2 requirements that an APU would not need to include a DPF if an OEM did not install the APU on a new tractor at the factory. The vast majority of APUs are installed at the dealer/distributor after the truck is sold when the vehicle owner requests an APU option. This presents a "loophole" in the Phase 2 regulation by allowing an APU manufacturer to claim that the tractors are no longer "new" and thus avoid installation of a DPF. Given the incremental cost of approximately $1800 as referenced in the heavy-duty Phase 2 RIA, the tractor's owner has a strong incentive to install an APU without the DPF at the dealer rather than having the DPF equipped APU installed at the truck assembly plant.

The current practice in the market of circumventing the intent of the rule will have significant consequences for both human health and GHG emissions, resulting in more than 75 metric tons (MT) of excess PM emissions with serious public health consequences, particularly for frontline communities. It is reasonable to assume that the APU will operate on average for 2000 hours per year. EPA's MOVES model estimates that APUs without DPFs emit 0.96 grams PM per hour while APUs with DPFs emit 0.02 grams PM per hour. The difference in emissions of 0.94 g/hr results in approximately 1880 grams of PM per year per APU. If 40,000 new APUs are sold each year, this would result in an additional 75.2 MT/yr of PM. This difference in PM emissions will have a significant negative impact on human health and air quality.

When CARB promulgated their rules for requiring DPFs on APUs, they applied it to 2007 and later trucks. Their intent was clear – with DPFs being installed as the latest technology to reduce PM on the tractor drive engine, it would be counter-productive to allow APUs on the same vehicle to operate without a DPF since this would emit more PM than the main engine with a DPF. It is our view that EPA clearly intended in 40CFR 1039.699 to follow the same logic, requiring DPFs to be installed on all APUs starting in MY 2024, and that this interpretation by the APU certificate holders creates an unintended "loophole" with significant public health, environmental equity and climate change impacts. We ask EPA to include language in the Phase 2 provisions in the Clean Trucks Regulation that would remediate this issue and ensure all APUs are equipped with DPFs when installed on MY 2024 and later on-highway HD trucks.

Technologies exist to ensure that MD gasoline engines can meet stringent standards like their diesel and natural gas counterparts. We encourage EPA to set tighter MD standards as the agency has indicated in the forthcoming Tier 4 light-duty regulation.

MECA supports regulations that 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. Engine-based technologies that can address cold start emissions include cylinder deactivation, electrical heaters and heated catalysts, hybridization and electronic variable valve timing. To control exhaust temperature under high load, technologies that can be applied to engines include exhaust gas recirculation, Miller cycle, cooled exhaust manifolds, electronic throttle control and advanced transmissions.

In addition to the engine technologies described above, several aftertreatment choices can be made to optimize emissions performance. 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. Recent advances have yielded high porosity, low thermal mass substrates with narrow pore size distributions, which enable high emissions reduction efficiency with less precious metal loading [49] [50]. 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 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 [51]. The aftertreatment systems were packaged with dual-wall insulated exhaust systems and fully aged to represent 120,000 miles of real-world operation. Even with 15 year old engine technology and limited engine calibration on one of the vehicles, 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 cost effective passive thermal management strategies, including dual-wall insulated exhaust or integrated exhaust manifolds, 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 [52], 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 was combined with cylinder deactivation and 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. Best in class Class 2b and 3 vehicles are currently reporting levels that are up to 75% below the Tier 3 NMOG+NOx certification standards.

PM and particle number emissions from MD and HD gasoline engines can be reduced further.

EPA 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. These standards were set at a stringency to require best available controls at the time being GPFs. Since 2019 high pressure fuel injection technology has further advanced to a point that it too can meet these stringent particle number limits. Europe implemented the PN limit for all vehicles in 2019, and China in 2020. India will implement it in 2023. 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 timeframe 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 combined with Euro 6d Real Driving Emission testing has motivated auto manufacturers to introduce these cleaner technologies on vehicles. Nearly all auto manufacturers that sell into the European or

Chinese markets are using particulate filters on gasoline direct injection vehicles as well as 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 (without a particulate filter) emitting 0.01 g/bhp-hr NOx [53]. 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% [54].

MECA supports the implementation of robust state-led diesel inspection and maintenance programs.

To ensure truck engines and aftertreatment systems are properly maintained and operating over their full useful life especially after the warranty has expired will require periodic inspection. This is particularly true for large class 7 and 8 tractor trailer trucks that may be on their second or third owner. MECA supports EPA's activities that encourage states to develop enforceable I/M programs for all vehicles.

MECA believes that sensors, already on vehicles, that are an essential part of the OBD system to monitor the NOx emissions from trucks over their operating lives can be used for the purpose of compliance monitoring in the future. 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 and EPA OBD requirements. Real Emissions Assessment Logging (REAL) requirements, which are now in force, require OEMs to store NOx and CO_2 emissions information on the vehicle and report to CARB periodically. MECA members offer telematics capability, that in the future, 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 emission 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 [55]. 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, CARB, EPA and EMA are participating in the Emission Measurement and Testing Committee (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, telematic reporting and sensor durability to assess their suitability for long-term compliance assurance.

CONCLUSION

In conclusion, MECA appreciates EPA's work in demonstrating pathways to meeting future heavy-duty low-NOx engine standards. We strongly support a modified Proposed Option 1 as outlined in our comments above. Proposed Option 1 along with our suggested modifications would result in cost effective air quality benefits for millions of Americans living in ozone and PM nonattainment areas. MECA believes that the standards in Proposed Option 1 are technically achievable for implementation by 2027 and stepping down, as proposed, in 2031. The test program at Southwest Research Institute has shown that engines equipped with advanced technologies paired with state-of-the-art aftertreatment systems can achieve levels consistent with the standards in Proposed Option 1 over certification cycles. Off-cycle testing over low load operation using real-world duty cycles, is showing that comfortable compliance margins exist in all three compliance bins. Furthermore, it has been demonstrated that low load and idle standards can be tightened to levels below those proposed. Finally, we support continued progress in reducing the GHG footprint from HD vehicles by considering the combination of technologies and fuels to enable stringent GHG standards. EPA staff should reconsider the generous credit provisions with respect to NOx credits and ZEV credit multipliers in light of the numerous OEM announcements of market introductions of EV trucks. Furthermore, stringent CO_2 standards being adopted in other global markets, such as Europe, will drive electric truck technology in the US into the market. All of these factors should be considered when revising the Phase 2 vehicle GHG limits and credit considerations. An underestimation of the EV penetration in light of generous credits could significantly increase emissions of NOx and CO_2 from combustion powered trucks. 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.

CONTACT:
Rasto Brezny
Executive Director
Manufacturers of Emission Controls Association
2101 Wilson Blvd.
Suite 530
Arlington, VA 22201
Tel.: (202) 296-4797
E-mail: rbrezny@meca.org

References

[1] MECA, "MOVES Inventory Modeling of a Potential Cleaner Trucks Initiative Scenario," 2020. Online at https://www.meca.org/wp-content/uploads/2022/01/CTI-MOVESInventoryModelingProjectSummary-0122Finalrev.pdf.
[2] Alpine Geophysics, "Air Quality Model Analysis of a Potential Cleaner Trucks Initiative Scenario," 2020.
[3] J. McCarthy, Jr., A. Matheaus, B. Zavala, C. Sharp and T. Harris, "Meeting Future NOx Emissions Over Various Cycles Using a Fuel Burner and Conventional Aftertreatment System (SAE-2022-01-0539)," SAE WCX, April 2022.
[4] T. Harris, R. Bellard, M. Muhleck and G. Palmer, "Pre-Heating the Aftertreatment System with a Burner (SAE 2022-01-0554)," SAE WCX, April 2022.
[5] A. Matheaus, G. Neely, C. Sharp, J. Hopkins and J. McCarthy, Jr., "Fast Diesel Aftertreatment Heat-up Using CDA and an Electric Heater (SAE 2021-01-0211)," SAE WCX, April 2021.
[6] EPA, "Test Results from EPA Diesel Engine Demonstration," 10 May 2022. [Online]. Available: https://www.regulations.gov/document/EPA-HQ-OAR-2019-0055-1082.
[7] Y. Kurimoto, R. Mishina, K. Kato, T. Aoki, K. Tanaka, T. Honda, A. Kaneda and C. Vogt, "Next Generation Diesel Particulate Filter for Future Tighter HDV/NRMM Emission Regulations (SAE 2022-01-0545)," SAE WCX, April 2022.
[8] C. Sharp, C. C. Webb, G. Neely, M. Carter, S. Yoon and C. Henry, "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 2017-01-0954)," SAE International Journal of Engines, vol. 10, no. 4, pp. 1697-1712, 2017.
[9] C. Sharp, C. C. Webb, S. Yoon, M. Carter and C. Henry, "Achieving Ultra Low NOx Emissions Levels with a 2017 Heavy-Duty On-Highway TC Diesel Engine - Comparison of Advanced Technology Approaches (SAE 2017-01-0956)," SAE International Journal of Engines, vol. 10, no. 4, pp. 1722-1735, 2017.
[10] C. Sharp, C. C. Webb, G. Neely, J. V. Sarlashkar, S. B. Rengarajan, S. Yoon, C. Henry and B. Zavala, "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 2017-01-0958)," SAE International Journal of Engines, vol. 10, no. 4, pp. 1736-1748, 2017.

[11] Mendoza Villafuerte, Pablo; Demuynck, Joachim; Bosteels, Dirk; Gioria, R; Selleri, T; Melas, A; Suarez-Bertoa, R; Perujo, A; Wilkes, T; Robb, L; Recker, P, "Ultra-Low NOx Emissions with Close-Coupled Emission Control System on a Heavy-duty Truck Application," in 30th Aachen Colloquium, 2021.

[12] J. Demuynck, P. Mendoza Villafuerte and D. Bosteels, "Ultra-low pollutant and CO2 emissions on demonstrator vehicles with advanced emission controls and sustainable renewable fuels," in 10th International Conference on Fuel Science, Aachen, 2022.

[13] Y. Ido, K. Kinoshita, C. Goto, H. Toyoshima, S. Hirose, E. Ohara, T. Honda, A. Kaneda, A. Wells and C. Vogt, "High-Porosity Honeycomb Substrate with Thin-Wall and High Cell Density Using for SCR Coating to Meet Worldwide Tighter Emission Regulations (SAE 2022-01-0550)," in SAE WCX, Detroit, MI, 2022.

[14] A. Salvi, F. Redon, D. Youngren and L. Fromm, "Low CO2, Ultralow NOx Heavy Duty Diesel Engine: Experimental Results (SAE 2022-01-0426)," SAE WCX, April 2022.

[15] MECA, "Technology Feasibility for Heavy-Duty Diesel Trucks in Achieving 90% Lower NOx Standards in 2027," 2020. Online at https://www.meca.org/wp-content/uploads/resources/MECA_2027_Low_NOx_White_Paper_FINAL.pdf.

[16] MECA, "Technology Feasibility for Model Year 2024 Heavy-Duty Diesel Vehicles in Meeting Lower NOx Standards," 2019. Online at https://www.meca.org/wp-content/uploads/resources/MECA_MY_2024_HD_Low_NOx_Report_061019.pdf.

[17] Navistar, "Final Scientific/Technical Report for SuperTruck Project: Development and Demonstration of a Fuel-Efficient, Class 8 Tractor & Trailer Engine System," 2016.

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

[19] J. Brin, J. Keim, E. Christensen, S. Holman and T. Waldron, "Applying a Driven Turbocharger to Improve Diesel NOx Conversion," in SAE WCX, Detroit, MI, 2022.

[20] F. Dhanraj, M. Dahodwala, S. Joshi, E. Koehler, M. Franke and D. Tomazic, "Evaluation of 48V Technologies to Meet Future CO2 and Low NOx Emission Regulations for Medium Heavy-Duty Diesel Engines (2022-01-0555)," in SAE WCX, Detroit, MI, 2022.

[21] CARB, "Draft Technology Assessment: Heavy-Duty Hybrid Vehicles," 2015.

[22] C. Zhang, E. Miller, A. Kotz, K. Kelly and M. Thornton, "Characterization of Medium- and Heavy-Duty Vehicle Operations from In-Use Data: An Analysis of Starts, Soak Time, and Warm-Up Duration," Golden, CO, 2019.

[23] F. Posada, H. Badshah and F. Rodriguez, "In-use NOx emissions and compliance evaluation for modern heavy-duty vehicles in Europe and the United States," 2020.

[24] G. Passavant, "Summary and Analysis of 2000-2015 Model Year IUVP Evaporative and Refueling Emission Data," 2017.

[25] EPA, "Tier 3 Motor Vehicle Emission and Fuel Standards," 28 April 2014. [Online]. Available: https://www.govinfo.gov/content/pkg/FR-2014-04-28/pdf/2014-06954.pdf.

[26] 40 CFR 85.020.

[27] PRWeb, "ROUSH CleanTech and Blue Bird First to Achieve Certification to 2022 Heavy Duty Refueling Standard," 2 May 2022. [Online]. Available: https://www.prweb.com/releases/roush_cleantech_and_blue_bird_first_to_achieve_certification_to_2022_heavy_duty_refueling_standard/prweb18651222.htm.

[28] 40 CFR Part 1037.130, 1037.621, 1037.622.

[29] B. Bunting, K. More, S. Lewis and T. Toops, "Exhaust Phosphorus Chemistry and Catalyst Poisoning," in 2004 Department of Energy Diesel Engine Emissions Reduction Conference, 2004.
[30] A. Williams, J. Luecke, R. L. McCormick, R. Brezny, A. Geisselmann, K. Voss, K. Hallstrom, M. Leustek, J. Parsons and H. Abi-Akar, "Impact of Biodiesel Impurities on the Performance and Durability of DOC, DPF and SCR Technologies," SAE International Journal of Fuels and Lubricants, vol. 4, no. 1, pp. 110-124, 2011.
[31] M. Lance, A. Wereszczak, T. J. Toops, R. Ancimer, H. An, J. Li, L. Rogoski, P. Sindler, A. Williams, A. Ragatz and R. L. McCormick, "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, vol. 9, no. 3, pp. 683-694, 17 October 2016.
[32] A. Williams, R. McCormick, M. Lance, C. Xie, T. Toops and R. Brezny, "Effect of Accelerated Aging Rate on the Capture of Fuel-Borne Metal Impurities by Emissions Control Devices," SAE International Journal of Fuels and Lubricants, vol. 7, no. 2, pp. 471-479, 2014.
[33] T. L. Alleman, L. Fouts and G. Chupka, "Quality Parameters and Chemical Analysis for Biodiesel Produced in the United States in 2011," National Renewable Energy Laboratory. NREL/TP-5400-57662, Golden, CO., 2013.
[34] T. L. Alleman, L. Fouts and E. D. Christensen, "Metals Analysis of Biodiesel Blends," National Renewable Energy Laboratory. NREL/TP-5400-72341, Golden, CO, 2019.
[35] T. L. Alleman, "Assessment of BQ-9000 Biodiesel Properties for 2020," National Renewable Energy Laboratory. NREL/TP-5400-79815, Golden, CO, 2021.
[36] CARB, "Regulations.gov," 25 February 2020. [Online]. Available: https://www.regulations.gov/document?D=EPA-HQ-OAR-2019-0055-0471.
[37] F. Posada, A. Isenstadt and H. Badshah, "Estimated cost of diesel emissions-control technology to meet the future California low NOx standards in 2024 and 2027," 2020.
[38] F. Posada, S. Chambliss and K. Blumberg, "Costs of Emission Reduction Technologies for Heavy-Duty Diesel Vehicles," International Council on Clean Transportation, Washington, DC, 2016.
[39] CARB, "Heavy-Duty Low NOx Program Workshop: HD UL & Step 2 warranty," 23 January 2019. [Online]. Available: https://www.arb.ca.gov/msprog/hdlownox/files/workgroup_20190123/04-HD_UL_&_Step_2_warranty_WS01232019.pdf.
[40] S. Hu, C. Howard, D. Quiros, R. Ianni, W. Sobieralski, W. Ham, H. Sun, B. Yang, C. Fehrenbacher, A. Vanzant, V. Sales, D. Chernich and T. Huai, "Overview of CARB's Truck and Bus Surveillance Program (TBSP): Findings and Implications," in 29th CRC Real World Emissions Workshop, Long Beach, 2019.
[41] CARB, "Carl Moyer Program Guidelines," 20 June 2017. [Online]. Available: https://www.arb.ca.gov/msprog/moyer/guidelines/current.htm.
[42] 40 CFR Parts 69, 80, and 86, "Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements," Federal Register, pp. 5002-5193, 2001.
[43] U.S. EPA, "Menu of Control Measures for NAAQS Implementation," 20 October 2017. [Online]. Available: https://www.epa.gov/sites/production/files/2016-02/documents/menuofcontrolmeasures.pdf.

[44] CARB, "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," 2019.
[45] CARB, "California Air Resources Board Staff Report on the Warranty Cost Study for 2022 and Subsequent Model Year Heavy-Duty Diesel Engines," 2021.
[46] N. Lutsey, "Integrating electric vehicles within U.S. and European efficiency regulations," 2017.
[47] A. Jenn, I. L. Azevedo and J. J. Michalek, "Alternative-fuel-vehicle policy interactions increase U.S. greenhouse gas emissions," Transportation Research Part A: Policy and Practice, vol. 124, pp. 396-407, 2019.
[48] R. Minjares and J. Hannon, "Adapting US heavy-duty vehicle emission standards to support a zero-emission commercial truck and bus fleet," 2022.
[49] T. Asako, D. Saito, T. Hirao and E. Popp, "Achieving SULEV30 Regulation Requirement with Three-Way Catalyst on High-Porosity Substrate while Reducing Platinum Group Metal Loading (SAE 2022-01-0543)," in SAE WCX, Detroit, MI, 2022.
[50] J. Warkins, T. Tao, M. Shen and S. Lyu, "Application of Low-Mass Corning FLORA Substrates for Cold-Start Emissions Reduction to Meet Upcoming LEV III SULEV30 Regulation Requirement (SAE 2020-01-0652)," in SAE WCX, Detroit, MI, 2020.
[51] J. W. Anthony and J. E. Kubsh, "The Potential for Achieving Low Hydrocarbon and NOx Exhaust Emissions from Large Light-Duty Gasoline Vehicles," in SAE Technical Paper 2007-01-1261, 2007.
[52] U.S. EPA, "EPA," March 2013. [Online]. Available: https://www.epa.gov/regulations-emissions-vehicles-and-engines/proposed-rule-and-related-materials-control-air-pollution.
[53] I. Khalek, H. Badshah, V. Premnath and R. Brezny, "Solid Particle Number and Ash Emissions from Heavy-Duty Natural Gas and Diesel w/SCRF Engines," in SAE Technical Paper 2018-01-0362, 2018.
[54] J. Yang, P. Roth, T. D. Durbin, K. C. Johnson, D. R. Cocker, III, A. Asa-Awuku, R. Brezny, M. Geller and G. Karavalakis, "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, vol. 52, no. 5, pp. 3275-3284, 2018.
[55] Y. Kawamoto, Y. Todo, H. Shimokawa, K. Aoki, M. Kawai and K. Ide, "Development of High Accuracy NOx Sensor," in SAE Technical Paper 2019-01-0749, 2019.
[56] C. M. Allen, M. C. Joshi, D. B. Gosala, G. M. Shaver, L. Farrell and J. McCarthy, "Experimental Assessment of Diesel Engine Cylinder Deactivation Performance During Low-Load Transient Operations," International Journal of Engine Research, 2019.
[57] MECA, "Technology Feasibility for Model Year 2024 Heavy-Duty Diesel Vehicles in Meeting Lower NOx Standards," 2019.
[58] M. Joshi, D. Gosala, C. Allen, S. Srinivasan, A. Ramesh, M. VanVoorhis, A. Taylor, K. Vos, G. Shaver, J. McCarthy Jr, L. Farrell and E. D. Koeberlein, "Diesel Engine Cylinder Deactivation for Improved System Performance over Transient Real-World Drive Cycles," in SAE Technical Paper 2018-01-0880, 2018.
[59] G. Neely, C. Sharp, M. Pieczko and J. E. McCarthy, "Simultaneous NOX and CO2 Reduction for Meeting Future CARB Standards Using a Heavy-Duty Diesel CDA-NVH Strategy," SAE International Journal of Engines, vol. 13, no. 2, 2020.

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

[61] U.S. Department of Energy, "2018 Annual Merit Review Vehicle Technologies Office Results Report," 2018.

[62] F. Posada, S. Chambliss and K. Blumberg, "Costs of Emission Reduction Technologies for Heavy-Duty Diesel Vehicles," International Council on Clean Transportation, Washington, DC, 2016.

[63] C. W. Tanner, K. Twiggs, T. Tao, D. Bronfenbrenner, Y. Matsuzono, S. Otsuka, Y. Suehiro and H. Koyama, "High Porosity Substrates for Fast-Light-Off Applications," in SAE Technical Paper 2015-01-1009, Detroit, 2015.

[64] A. Walker, Catalyst-Based Emissions Control Solutions for the Global HDD Market – What Does the Future Hold?, Gothenburg, 2016.

[65] M. Kruger, S. Bareiss, A. Kufferath, D. Naber, D. Ruff and H. Schumacher, "Further Optimization of NOx Emissions Under the EU 6d Regulation," in Stuttgart International Symposium on Automotive and Engine Technology, Stuttgart, Germany, 2019.

[66] C. S. Hendrickson, D. Upadhyay and M. Van Nieuwstadt, "Selective Catalytic Reduction Control with Multiple Injectors," in SAE Technical Paper 2017-01-0943, Detroit, 2017.

[67] U.S. EPA, "Impact of Mobile Source Emissions on Air Quality," 31 May 2017. [Online]. Available: https://www.epa.gov/sites/production/files/2017-06/documents/05312017-epa-presentation.pdf.

[68] Y. Kawamoto, Y. Todo, H. Shimokawa, K. Aoki, M. Kawai and K. Ide, "Development of High Accuracy NOx Sensor," in SAE Technical Paper 2019-01-0749.

[69] H. Badshah, F. Posada and R. Muncrief, "Current State of NOx Emissions from In-Use Heavy-Duty Diesel Vehicles in the United States," 2019.

[70] A. Ragatz and M. Thornton, "Aerodynamic Drag Reduction Technologies Testing of Heavy-Duty Vocational Vehicles and a Dry Van Trailer, Appendix C," 2016.

[71] C. Sharp, CARB Low NOx Development and Demonstration Programs at SwRI Progress Update, Detroit, MI: WCX 19: SAE World Congress Experience, 2019.

[72] CARB, "CEPAM: 2016 SIP - Standard Emission Tool," 2018. [Online]. Available: https://www.arb.ca.gov/app/emsinv/fcemssumcat/cepam_emseic_query_v5.php?F_YR1=2008&F_YR2=2018&F_YR3&F_YR4&F_YR5&F_YR6&F_YR7&F_YR8&F_YR9&F_YR10&F_YR11&F_YR12&F_YR13&F_YR14&F_YR15&F_YR16&F_YR17&F_YR18&F_YR19&F_YR20&F_YR21&F_YR22&F_YR23&F_YR24&F_BYR=2012&F_S.