COMMENTS OF THE
MANUFACTURERS OF EMISSION CONTROLS ASSOCIATION
ON CALIFORNIA AIR RESOURCES BOARD'S PROPOSED LOW-NOx
OMNIBUS REGULATION

August 25, 2020

The Manufacturers of Emission Controls Association (MECA) would like to provide comments in strong support of the California Air Resources Board's (CARB) proposed rulemaking to set more stringent standards and other requirements for the medium- and heavy-duty truck sector and reduce the amount of harmful emissions generated from on-road mobile sources. We support CARB's ongoing leadership in the effort to reduce the environmental footprint of transportation to meet the state's SIP and climate goals, including technology advancing regulations that provide pathways to clean up the heavy-duty vehicle fleet. We believe an important opportunity exists to continue to reduce criteria emissions and greenhouse gases from medium- and heavy-duty engines and vehicles through the application of advanced technologies on engines and powertrains that can be combined with low carbon fuels and electrification as system solutions to environmental challenges.

MECA is an industry trade association of the world's leading manufacturers of clean mobility technology. Our members have nearly 50 years of experience and a proven track record in developing and commercializing emission control, efficiency and electric technology for a wide variety of on-road and off-road vehicles and equipment in all world markets. Our members provide the technologies that enable heavy-duty on-road vehicles to meet the most stringent NOx and PM emission standards, as well as electrification and all-electric technologies that reduce emissions of all pollutants, criteria and climate, and allow commercial vehicles to be the cleanest possible. Our industry has played an important role in the environmental success story associated with light- and heavy-duty vehicles in the United States and has continually supported CARB's efforts to develop innovative, technology-advancing, regulatory programs to deal with air quality and climate challenges.

In addition to offering our strong support of the Omnibus, MECA would like to highlight the following suggestions, which are explained in greater detail in the text that follows, that we feel will strengthen the regulation:

1. We encourage CARB to explore a collaborative demonstration program that could be undertaken in the years leading up to implementation of the Omnibus 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.
2. We suggest that CARB align light-heavy-duty diesel engine durability requirements with the larger engine classes and cap useful life at 12 years instead of the 15 year requirement currently proposed.
3. We recommend that HD ZEV NOx credits issued for electric trucks under the Omnibus be limited to only the earliest years of implementation to provide flexibilities to truck manufacturers to introduce the cleanest diesel trucks in the state as early as possible while

limiting potential excess NOx emissions.

4. We urge CARB to review the U.S. EPA final CTI rule and consider harmonizing tailpipe limits and evaporative and refueling control requirements for this sector as part of future heavy-duty Omnibus amendments.
5. We suggest that CARB consider funding an on-road demonstration of the low-NOx engine from SwRI after installation in a vehicle.
6. We encourage CARB to continue development of a robust heavy-duty I/M program.

Further NOx Reductions are Necessary

Inventory and Air Quality Modeling

Hundreds of millions of people in the U.S. still breathe unhealthy air, and many live in California, including 12 million residents in regions that are in ozone and/or PM nonattainment that would benefit from a lower NOx limit on heavy-duty engines. In a 2017 meeting of the Mobile Source Technical Review Subcommittee, U.S. EPA presented inventory projections showing large contributions of heavy-duty vehicle NOx emissions to ambient ozone and secondary $PM_{2.5}$ levels in 2025 (U.S. EPA, 2017). California estimates that on-road heavy-duty vehicles contribute to 31% of all statewide NOx emissions, which is the largest NOx source category in the state (CARB, 2018).

MECA recently co-funded an emission inventory and air quality modeling analysis based on the emission limit values and durability requirements proposed by CARB to quantify the air quality benefits if a national standard were set by U.S. EPA under the CTI to align with the CARB proposed limits and implementation dates (MECA, 2020; Alpine Geophysics, 2020). The analysis did not incorporate the compliance program changes or warranty revisions into our model assumptions. The foundation of the evaluation was the current U.S. EPA inventory projection for 2028. The 2028 inventory projection is that of the 2016v1 emissions modeling platform. It is a product from the agency's National Emissions Inventory Collaborative and includes a full suite of the base year (2016) and the projection year (2023 & 2028). This part of the analysis is referred to as the "2028 Base Case" inventory in this study and corresponds closely with a 2027 implementation date for the CTI rule. From that inventory foundation, two new inventory scenarios were developed as follows.

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

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

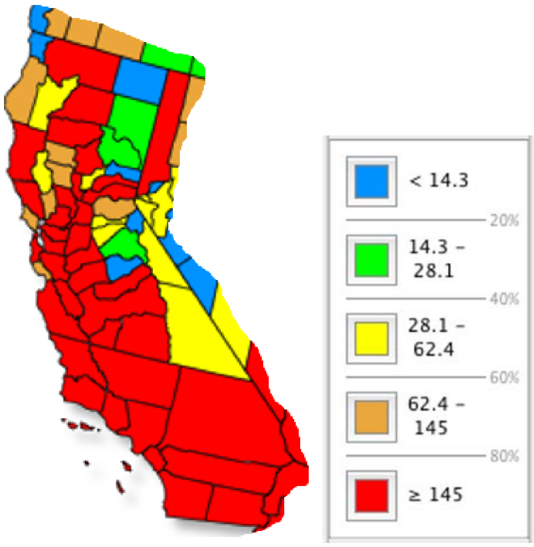

Figure 1. Federal NOx Standard Annual Benefit in California in 2035 (tons reduced)

Results from the inventory analysis show that the new modeled FTP limits would result in a California statewide reduction of nearly 35,000 tons per year of NOx in 2035. When taking a more refined look at the location of the NOx benefits at the county level, those counties currently in nonattainment or maintenance with the 2015 ozone NAAQS will receive some of the highest NOx reductions (e.g. > 145 tons NOx in 2035) from a 0.02 g/bhp-hr heavy-duty engine FTP standard. These estimates likely represent conservative values of real-world NOx reductions because the current version of MOVES does not have the latest emission factors representing low-load and low-speed truck operation. U.S. EPA is updating the next version of MOVES to represent emissions in these challenging duty-cycles more accurately. This update is expected to bring real world NOx emissions down further once the emission factors of future certification that includes a low-load cycle are factored into the model. In addition to NOx reductions, the proposed standards are projected to yield reductions in VOCs and carbon monoxide in 2035.

The companion air quality analysis concluded that ozone levels would decline in several California counties in 2035 as a result of the NOx reductions estimated by the inventory analysis discussed above. 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 San Bernardino. In addition, the model predicts that 8-hour ozone design values would decline by 5 ppb or more in the counties of El Dorado, Fresno, Kern, Placer, Riverside, Sacramento, and (as already mentioned) San Bernardino. It is important to note that even though the 2015 ozone NAAQS was finalized at 70 ppb, U.S. EPA's Clean Air Scientific Advisory Committee (CASAC) in 2015 supported a range of 60-70 ppb for the 8-hour primary ozone standard. Prior to applying the projected CTI strategy, nearly 300 monitoring sites in the U.S. are projected to have 8-hour ozone design values between 60 and 70 ppb, and the proposed CTI strategy will reduce these by an average of 2.35 ppb and up to a max of 5 ppb.

Environmental justice communities

Communities near freeways, ports and freight corridors experience acute environmental impacts, including air pollution and noise, due to high heavy-duty truck traffic. Many studies have shown health risks related to living in areas with air quality affected by goods movement emissions. Many of these communities include high populations of mostly low-income and minority citizens, which raises environmental justice concerns. Some of the highest county-level NOx reductions from a more stringent heavy-duty NOx standard are found in major metropolitan regions and along highways involved in goods movement and populated by EJ communities.

MECA Supports CARB'S NOx Stringency and Final Implementation Dates

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 in 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. Several years ago, CARB initiated its rulemaking process on the next set of heavy-duty engine standards, including feasibility demonstrations and technical working group discussions. The technical work process started in 2013 when 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. Finalization of the proposed regulatory provisions will provide certainty to suppliers and their OEM customers. Suppliers have been making investments in research and development to prepare for the future needs of their customers. MECA appreciates all of the time and effort that CARB staff put into the regulatory process for this important regulation. The number of workgroup meetings, workshops and technical advisory group meetings has been unprecedented and contributed to a transparent process of information collection and sharing. The regulatory process around this proposed rule has had the greatest amount of stakeholder input and CARB staff commitment to data gathering, and we thank staff for their dedication in receiving and incorporating feedback from a broad range of stakeholders.

MECA supports CARB's proposed phased-in implementation dates beginning with MY 2024, continuing in MY 2027, and fully phased in by MY 2031. The intermediate MY 2024 limits of 0.05 g/bhp-hr and final step down to an FTP limit of 0.02 g/bhp-hr in 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. In addition, MECA supports CARB's proposed PM standard of 0.005 g/bhp-hr on the FTP and RMC cycles for MY 2024 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 PM measurements at near zero levels. This more stringent standard will prevent backsliding by ensuring the best available DPFs remain an integral component in aftertreatment systems.

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

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

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

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

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

The Omnibus regulation will 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 the industry is motivated to work together to meet them. As part of this process, over the next four to six 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 OEM 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) Slight increase 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 10 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 10 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 several years. A more detailed discussion of the multiple technology pathways to achieving the emission limits proposed in this rule is provided below.

Technologies are now commercially available to meet a 0.02 g/bhp-hr FTP NOx standard by 2027

Engine technologies, advancements in engine calibration, thermal management, and advanced catalysts can be combined to enable engines plus aftertreatment systems to achieve FTP and RMC emissions below 0.02 g/bhp-hr NOx (MECA, 2020). Ongoing work by MECA members, SwRI and U.S. EPA is aimed at demonstrating emission levels that will provide sufficient compliance margins that OEMs need for full useful life durability. This includes testing funded by U.S. EPA, which is expected to be conducted in 2020 and 2021 and is aimed at optimizing the engine and aftertreatment system further improved from 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 engine plus aftertreatment system can achieve FTP emissions below 0.05 g/bhp-hr NOx by 2024. 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 at today's durability requirements by 2027. Figure 2 shows current and potential future aftertreatment layouts. Please note that the figure does not show the complement of NOx, temperature and ammonia sensors that will be used for OBD and dosing calibration to optimize NOx conversion over the SCRs. System S1 is based on 2019 engines in production today. Systems S2 and S3 are two examples that employ a twin SCR arrangement.

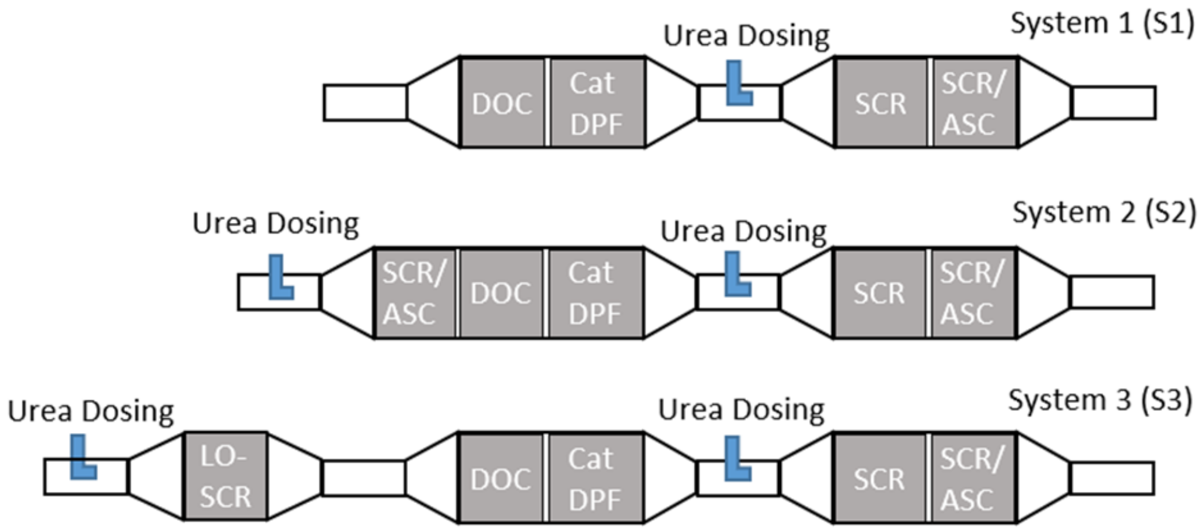

Figure 2. System configurations tested to demonstrate the feasibility of 2027 engine emissions.

Aftertreatment conversion models validated on fully aged catalysts and engine testing on dynamometers have demonstrated the ability to achieve NOx levels as low as 0.015 g/bhp-hr over the FTP and below 0.075 on the proposed LLC certification cycles using a preliminary engine calibration from SwRI (MECA, 2020). Over the past 7 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 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 a limit of 0.02 g/bhp-hr is a technologically achievable final standard for a national program by 2027.

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 Standards, and U.S. EPA envisions further penetration of additional technologies for trucks to meet future Phase 2 requirements beginning in 2021. At the same time, research undertaken by multiple teams as part of the Department of Energy's SuperTruck I program has demonstrated how these technologies can be combined to achieve a 16% boost in fuel economy and improved freight efficiency. Participants in the SuperTruck II program are in the process of demonstrating even greater gains in fuel and freight efficiency. Component suppliers have continued to innovate, and many technologies that were not even considered as compliance options in the Phase 2 rule are now likely to be deployed on limited engine families in 2024 and more broadly in 2027. Furthermore, engine efficiency technologies – such as cylinder deactivation, advanced turbochargers, and hybridization – have also been demonstrated in combination with advanced aftertreatment technologies on heavy-duty diesel engines. Testing has shown the ability of several advanced engine technologies to be optimized to improve fuel efficiency while increasing exhaust temperature in diesel engine exhaust, which improves SCR NOx reduction performance (Sharp, CARB Low NOx Development and Demonstration Programs at SwRI Progress Update, 2019).

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

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

Since 2010 the predominant 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 3). 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.

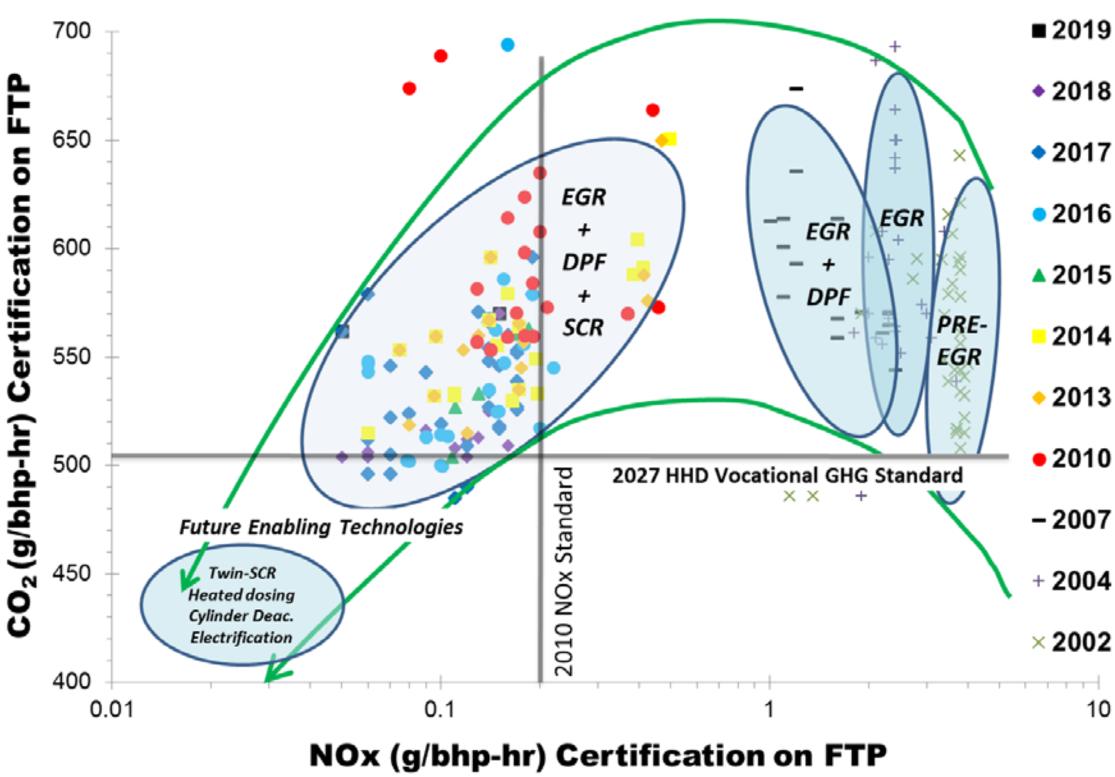

Figure 3. Heavy-Duty Engine Certification Test Data for NOx and CO_2.

Numerous technology options exist for achieving the proposed emission standards and compliance provisions

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

Cylinder Deactivation and Variable Valve Actuation

Cylinder deactivation (CDA) is an established technology on light-duty vehicles, with the primary objective of reducing fuel consumption and CO_2 emissions. This technology combines hardware and software computing power to, in effect, "shut down" some of an engine's cylinders, based on the power demand, and keep the effective cylinder load in an efficient portion of the engine map without burning more fuel. Based on decades of experience with CDA on passenger cars and trucks, CDA is now being adapted to heavy-duty diesel engines. On a diesel engine, CDA is programmed to operate differently than on gasoline engines, with the goal of the diesel engine running hotter in low load situations by having the pistons that are firing do more work. This programming is particularly important for vehicles that spend a lot of time in creep and idle operation modes. During low load operation, CDA has resulted in exhaust temperatures increasing by 50°C to 100°C when it is most needed to maintain effective conversion of NOx in the SCR. In some demonstrations, CDA has been combined with a 48V mild hybrid motor with launch and sailing capability to extend the range of CDA operation over the engine, and this may deliver multiplicative CO_2 reductions from these synergistic technologies (MECA, 2020).

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

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 (Navistar, 2016). In addition to affecting the power density of the engine, turbochargers play a significant role in NOx and CO_2 regulations compliance. Continuous improvement in turbocharger technology is making it possible to run very lean combustion (high air/fuel ratios), which is efficient. This improvement allows for very low particulate generation and even low engine-out NOx.

Turbocompounding

Turbocompounding is a variant of turbocharger technology that allows for the mechanical energy from the exhaust gas to be extracted and added to the engine crankshaft through a transmission. Mechanical turbocompounding has been employed on some commercial diesel engines, and U.S. EPA estimated penetration to reach 10% in the U.S. by the time the Phase 2 GHG Regulation is fully implemented in 2027 (U.S. EPA, 2016). An early 2014 version of a turbocompound-equipped engine was used during the first stage of testing at SwRI under the CARB HD Low NOx Test Program, and the results from this engine with advanced aftertreatment have been summarized in several SAE technical papers (Sharp, et al., 2017-01-0958, 2017; Sharp, et al., 2017-01-0954, 2017; Sharp, Webb, Yoon, Carter, & Henry, 2017). While turbocompounding has the potential to reduce fuel consumption, it can result in lower exhaust temperatures that can challenge aftertreatment performance. Therefore, it is important to consider turbocompound designs that incorporate bypass systems during cold start and low load operation or electrically driven turbocompounding systems where the unit can be placed after the aftertreatment system.

Driven turbochargers

Driven 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. Testing has shown that routing engine exhaust to the aftertreatment by bypassing a turbocharger is one of the most effective methods to heat up the aftertreatment (MECA, 2020).

Electrification: Mild Hybridization

48-volt mild hybrid electrical systems and components are expected to make their way onto heavy-duty vehicles in the near future. These 48-volt systems can be found on many light-duty vehicle models (primarily in Europe) from Mercedes, Audi, VW, Renault and PSA. In the U.S., FCA is offering a 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 are employing 48-volt technologies as they attempt to demonstrate trucks with greater than 55% brake thermal efficiency.

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

Mild hybridization covers a range of configurations, but a promising one includes an electric motor/generator, regenerative braking, electric boost and advanced batteries. Stop/start deployment also provides a thermal management benefit to the aftertreatment by preventing cooling airflow through the aftertreatment during hot idle conditions. In this way, 48-volt mild hybridization is complementary technology to CDA and start-stop capability, allowing the combination of multiple technologies on a vehicle to yield synergistic benefits and justify the cost. By shutting off the engine at idle or motoring using start/stop, micro hybrid technology can help to maintain aftertreatment temperature by avoiding the pumping of cold air through the exhaust. Capturing braking energy and storing it in a small battery for running auxiliary components when the engine is off offers another CO_2 reducing strategy for OEMs to deploy.

In lighter medium-duty applications, advanced start-stop systems have been developed that use an induction motor in a 48-volt belt-driven starter-generator (BSG). When the engine is running, the motor, acting as a generator, will charge a separate battery. When the engine needs to be started, the motor then applies its torque via the accessory belt and cranks the engine instead of using the starter motor. The separate battery can also be recharged via a regenerative braking system. In addition to the start-stop function, a BSG system can enhance fuel economy even during highway driving by cutting off the fuel supply when cruising or decelerating. Such systems can also be designed to deliver a short power boost to the drivetrain. This boost is typically 10 to 20 kW and is limited by the capacity of the 48V battery and accessory belt linking the motor to the crankshaft. New designs are linking the BSG directly to the crankshaft and allowing additional power boost of up to 30kW to be delivered, giving greater benefits to light and medium commercial vehicles (MECA, 2020).

Electrification: Full hybridization and electric vehicles

Full hybrid configurations are currently found on several models of light-duty passenger cars and light trucks in the U.S. and a limited number of medium-duty trucks. These include models that can also be plugged-in to enable some all-electric operation, usually described as all-electric range (AER). A full hybrid can enable electrification of many of the components described above for mild hybrid vehicles, but the higher voltages allow for more parts to be electrified and to a larger degree. Full hybrids implement larger electric motors and batteries, which support greater acceleration capability and regenerative braking power. Mild hybridization is well-suited to heavy-duty vehicles used for long-haul transportation because of the limited fuel economy of a full hybrid at highway speeds. Full hybridization and electrification are more practical for small heavy-duty vehicles (e.g., Class 4-6) that do not travel long distances or operate for long periods without returning to a central location. Full hybrid vehicles have made the highest penetration into parcel delivery, beverage delivery and food distribution vehicles because they can take advantage of regenerative braking in urban driving (CARB, 2015). We expect to see some application of strong hybrids combined with a low NOx engine to reduce CO_2 emissions in several vocational applications. Integrated electric drivetrain systems, consisting of a fully qualified transmission, motor and power electronics controller, are now commercially available. With power levels of over 160kW and the ability to meet high torque requirements, these systems enable electrification of medium-duty commercial vehicles. There is also an increasing number of electric drivetrain solutions up to 300kW that are suitable for Class 8 vehicles that can be used with either battery or fuel cell power sources (MECA, 2020).

As noted above, the types of technologies that enable electrified heavy-duty vehicles are already commercially available with more anticipated by 2027. Some barriers that remain, such as infrastructure needs, should be addressed through other state and national efforts. MECA supports the inclusion of revised certification procedures that allow for a better demonstration of the criteria pollutant benefits offered by certain powertrain technologies. Current engine certification procedures for criteria pollutants do not accurately account for the benefits of electrified technologies, including hybrid electric vehicles and stop-start systems. MECA supports alternative test methods, such as those proposed in U.S. EPA's Heavy-duty Phase 2 GHG technical amendments, to be available for certification of California engines and vehicle systems to criteria emission standards. For example, MECA supports powertrain testing, powertrain-in-the-loop, and engine-in-the-loop test methods.

MECA supports the proposed changes to certification and in-use requirements that achieve low NOx emissions in the real world

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 (Zhang, Miller, Kotz, Kelly, & Thornton, 2019). Results from this report provide some insights into the causes for NOx emission reduction challenges due to real world operation.

Some observations from this work 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.

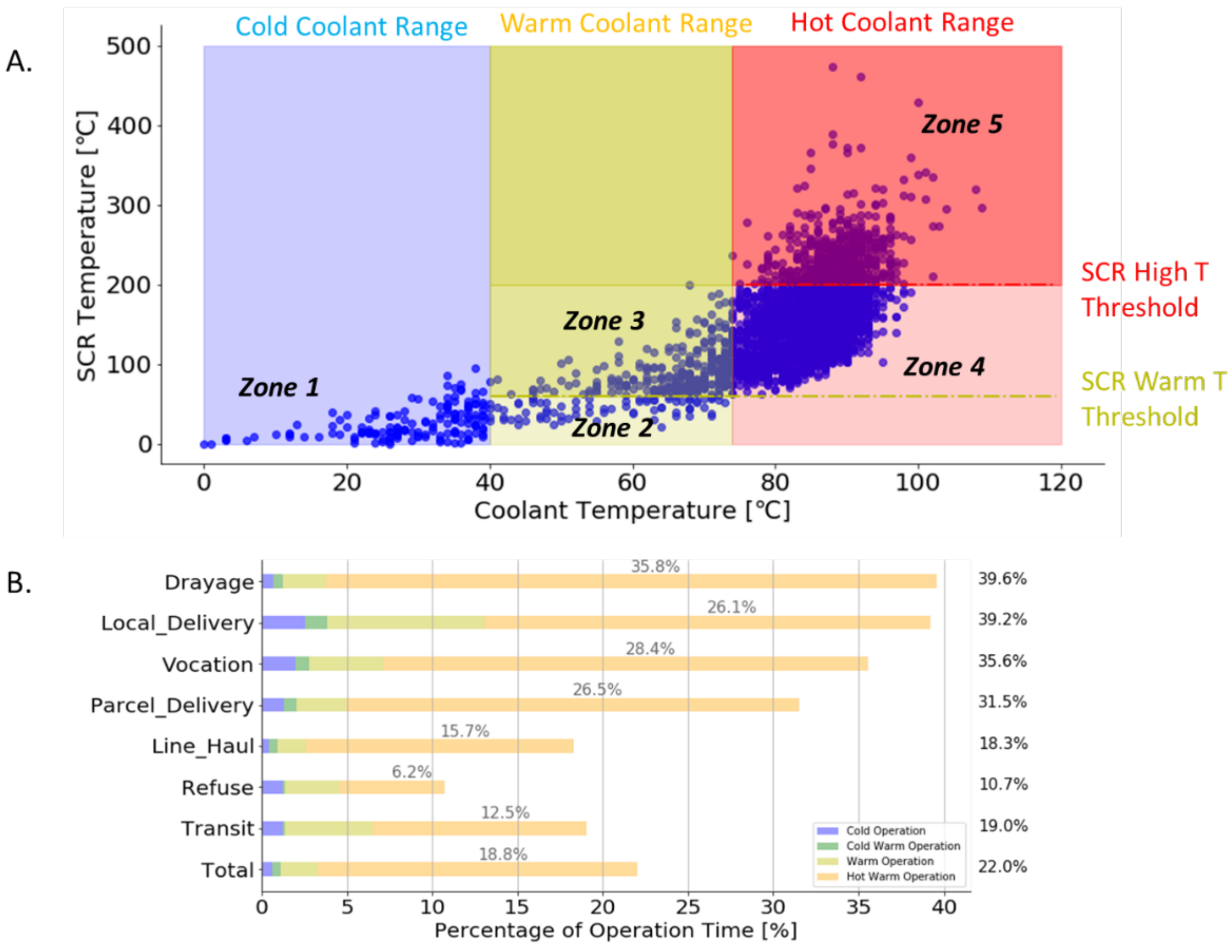

Figure 4. A) Number and type of engine start based on coolant temperature and SCR temperature. B) Percentage of time spent at different coolant-exhaust temperature conditions. Note: Engine starts defined as "cold" when coolant temp ≤ 40℃, warm-cold when coolant temp is between 40-75℃ and SCR temp is ≤ 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℃.

MECA supports the addition of the Low Load Cycle as part of engine certification

The Omnibus proposal aims to address the in-use "loophole" through two revised regulatory requirements – one affecting certification and one affecting in-use testing. 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 2024 for engine certification and the proposed emission limit of 0.2 g/bhp-hr in the early implementation of 2024-2026 and further tightening this limit to 0.05 g/bhp-hr in 2027 and beyond.

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 CARB 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 proposed LLC limits. Testing of the Stage 1 and Stage 3 engine and aftertreatment systems have met or exceeded the LLC emission limits proposed by CARB 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 replacement of the NTE with a moving average windows approach during in-use compliance testing

The proposal 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 (Posada, Badshah, & Rodriguez, 2020). 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. Therefore, MECA also supports CARB's proposal to phase-in data inclusion requirements for HDIUT and HDIUC that ensure in-use compliance testing is representative of all engine operation by MY 2027.

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 U.S. 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 laboratory-aged to an equivalent of 435,000 miles on a dynamometer over a speed-load trace from an actual drive cycle in Southern California. The driving cycle has been used by CARB for HDIUT 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 this real-world cycle, the system achieved a cycle average tailpipe NOx emission limit of 0.023 g/bhp-hr while being fuel consumption neutral to slightly more efficient than the baseline aftertreatment system.

SwRI then analyzed the window data using the proposed three bin approach and found that the system was comfortably below the limits being proposed for the three bins in 2027. The compliance margin on the highest power bin was about 25%, and the two lower power bins had compliance margins of 65% for the low power bin and 90% at idle. These results confirm the tremendous efficacy of the Stage 3 system for meeting the challenging low load operating conditions where they are needed the most such as in urban city centers.

MECA supports the implementation of a robust diesel inspection and maintenance program.

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 has been engaged in the heavy-duty I/M workshops and support CARB's activities to develop an I/M program.

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's HD-OBD requirements. Beginning in 2022, CARB will institute their Real Emissions Assessment Logging (REAL) requirements to store NOx and CO_2 emissions information on the vehicle and report to CARB staff periodically. MECA members offer telematics capability, that 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 (Kawamoto, et al., 2019). NOx sensors only operate above an exhaust temperature threshold to prevent water condensation and thermal shock of the ceramic element. This may make it difficult to measure NOx during low load and low speed operation. Manufacturers are developing more durable sensor designs and experimenting with sensor placement in the exhaust to minimize these limitations and extend the temperature range of their sensors and improve their durability. MECA supports

CARB's decision to hold current NOx sensor OBD thresholds until 2027 when the lowest NOx limits will come into force. We believe that further tightening of thresholds must consider sensor accuracy at low-NOx concentration, detection limits, and warranty cost implications considering the trade-off between accuracy and durability of the proposed threshold reduction.

MECA, CARB, U.S. 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 U.S. 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.

MECA supports technology-neutral and fuel neutral regulations. Technologies exist to ensure that MD gasoline engines can meet stringent standards like their diesel and natural gas counterparts.

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

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

Engines and aftertreatment systems have evolved significantly over the past 15 years and in fact, in support of the Tier 3 light-duty regulation (U.S. EPA, 2013), U.S. EPA tested a 2011 LDT4 pick-up truck with a 5.3L V8 engine that included a MECA supplied aftertreatment system. The aftertreatment consisted of advanced catalyst coating on 900 cpsi substrates in the close-coupled location as well as underfloor catalysts and was aged to 150,000 miles. The system achieved an FTP NMHC+NOx level of 18 mg/mile. We believe that these same technology approaches can be deployed on medium-duty gasoline engines to meet the same stringent emission levels being considered for medium-duty diesel engines.

Fuel neutral standards should be applied to PM emissions from HD gasoline engines in the spirit of having fuel neutral standards for this sector. CARB is proposing to tighten PM by 50% to 0.005 g/bhp-hr for diesel engines and MECA believes that would not require any change in technology but only serve as a backstop to prevent backsliding under a tighter NOx limit. As fuel efficiency standards tighten and GDI injection technology becomes more common on commercial vehicle engines, the PM emissions from medium and heavy-duty gasoline engines are likely to increase dramatically. The European Commission, China and India have adopted a particle number emission standard for light-duty vehicles powered by gasoline direct injection (GDI) engines as a part of their Version 6 light-duty emission standards. Europe implemented the PN limit for all vehicles in 2019, and China and India will implement it in 2020 and 2023, respectively. China will require all vehicles to meet this limit in 2023, including gasoline port fuel injected vehicles. This PN standard established a more stringent particle emission limit for GDI vehicles in the same timeframe as U.S. 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 6×10^{11} particles/km, measured using the European PMP particle measurement protocol and is approximately equivalent to 0.5 mg/mile. This European particle number limit will cause auto manufacturers to introduce cleaner technologies such as advanced fuel injection systems and/or gasoline particulate filters. Nearly all auto manufacturers that sell into the European or Chinese markets are using particulate filters on gasoline direct injection vehicles 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 (Khalek, Badshah, Premnath, & Brezny, 2018). Although this CNG engine emitted very low PM mass levels, the PN emissions were an order of magnitude greater than a low NOx diesel engine with a DPF. A GPF or DPF wall-flow filter provides the co-benefit of also reducing toxics and carcinogens like PAH that are associated with GDI and PFI PM by over 90% (Yang, et al., 2018).

We believe that an opportunity exists to significantly reduce VOC emissions from gasoline heavy-duty engines by expanding Onboard Refueling Vapor Recovery (ORVR) to incomplete HDGVs rated over 14,000 lbs. Gross Vehicle Weight Rating (GVWR). The U.S. EPA and CARB regulatory framework offers the most comprehensive evaporative control program in the world for chassis certified vehicles. On-Board Refueling and Vapor Recovery (ORVR) has been successfully implemented in the U.S. and Canada for over 25 years. There have been over 1600 tests conducted on in-use ORVR vehicles with an average reduction efficiency of 98%. The odometer readings on a large fraction of these vehicles exceeded 100,000 km. U.S. Tier 2 or California LEV II have reduced evaporative emissions by 90%, and U.S. Tier 3 or California LEV III are 98% effective in reducing evaporative VOC emissions. Engine-certified gasoline engines have missed a significant opportunity to reduce their VOC emissions, and MECA supports U.S. EPA's consideration of extending advanced canisters and ORVR systems to this category of engines and significantly reduce VOC emissions from these engines.

In these comments, we refer to HDGVs as heavy heavy-duty gasoline vehicles (HHDGVs) since almost all HHDGVs are produced in an incomplete configuration. Also, HDGVs between 8,501 and 14,000 lbs. GVWR will be referred to as light heavy-duty gasoline vehicles (LHDGVs). This definition is consistent with the terminology used by U.S. EPA in Tier 3. Today, both complete and incomplete HHDGVs are implementing Tier 3 evaporative requirements, and all complete HHDGVs will have ORVR by MY 2022. Incomplete HHDGVs are the only class of gasoline motor vehicles without refueling control. There should no longer be implementation concerns and, with the availability of cost-effective control technology, we believe that ORVR requirements and testing should be applied to this final category of on-road gasoline engines to control these VOC and air toxic emissions from HHDGVs. U.S. EPA has signaled their intent in proposing to tighten the refueling requirements for this category of heavy-duty gasoline engines under the CTI. We urge CARB to review the U.S. EPA final CTI rule and consider harmonizing evaporative refueling control requirements for this sector as part of future heavy-duty Omnibus amendments.

Diesel trucks can meet stringent emission limits over the course of longer lifetimes.

Extended Warranty and Durability Requirements

The evolution of the warranty and durability aspects of this proposal highlights the advantages of a well-designed public rulemaking process that allows all stakeholders to provide comments, suggestions and data. We thank staff for critically reviewing all of the information provided from a broad group of stakeholders to decide upon the proposed warranty and durability requirements. MECA appreciates the significant effort of CARB staff to understand the complexity of this issue and incorporate suggestions throughout the rulemaking process based on input from the supplier community. We understand CARB'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.

We believe that CARB's final proposed Step 2 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 and extending the final implementation date to 2031 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 CARB's decision to retain an hourly limit 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. Finally, as U.S. EPA's Cleaner Trucks Initiative (CTI) has not yet been proposed, we encourage continued collaboration and discussion between CARB and U.S. EPA as the regulatory development of the CTI continues so that California and federal durability and warranty requirements can be harmonized on a feasible timeline that is based on the best available data. We support CARB's proposal to slightly increase the emission standards out to longer durability periods to account for possible deterioration beyond the currently demonstrated level of 435,000 equivalent miles. Later this year, OTAQ staff at U.S. EPA is planning a longer durability demonstration to 850,000 equivalent miles of an aftertreatment system similar to that tested by SwRI.

During development of the Omnibus, MECA worked with NREL to review FleetDNA data from real trucks to estimate and project annual vehicle time of operation and combine that information with the best engineering judgment of our members to provide feedback to CARB staff. NREL provided operation and use statistics as a function of vocation for Class 6 through Class 8 vocational and line-haul vehicles. These data were helpful in estimating annual time of operation, but there are still some characteristics that may have been underrepresented by the dataset, including vehicles operated by second and third owners. Therefore, we would like to explore additional collaborative efforts, such as a demonstration program that could be undertaken by CARB, EPA, MECA, EMA and other stakeholders in the years leading up to implementation of the Omnibus requirements. Such efforts would be designed at 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 after the warranty expires. 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. Furthermore, suppliers do not have data on engine and aftertreatment components beyond today's warranty requirements (e.g., past 100,000 miles). 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. With respect to warranty, suppliers are not able to project the number of warranty claims they can expect to receive for future extended warranty periods, which makes it difficult to estimate the cost impact to them. 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. Thus, MECA appreciates CARB's compromise in reducing the proposed useful life to the current values that phase in from 10 years to 12 years in MY 2031 for medium-heavy-duty and heavy-heavy-duty diesel engines. However, despite the potential inconsistency with LEV III requirements, MECA suggests that CARB align light-heavy-duty diesel engine durability requirements with these larger engines and cap useful life at 12 years instead of the 15 year requirement currently proposed.

Fuel Quality

Impacts of fuel quality on future aftertreatment systems

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

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

As described above, an aftertreatment architecture likely to be employed to meet 2027 FTP and LLC standards will include a twin SCR arrangement with a close-coupled SCR that is upstream of today’s aftertreatment systems. The close-coupled SCR will be mainly exposed to SO_2 rather than SO_3, the latter being a more severe poison. Research suggests that sulfur effects on the close-coupled SCR can be reversed by heating the catalyst to 500°C, which can be achieved through late post injection or other engine thermal management strategies, including cylinder deactivation and variable valve actuation (VVA) strategies. 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.

Subsequent to the Low-NOx Omnibus Board hearing, U.S. EPA will be conducting accelerated aging and durability demonstration out to 850,000 mile equivalent useful life using a new aging protocol being developed with industry partners and MECA. The results of this program will help to inform about the long-term impacts of fuel sulfur on SCR catalysts. Aging experience from catalyst manufacturers suggests that the greatest impact may be on the close-coupled SCR since this is closest to the engine and sees the highest temperature and the major portion of lube oil metal exposure. The downstream, underfloor SCR is somewhat protected from fuel metals by the DOC and DPF. However, it will see higher temperatures during DPF regeneration.

Some metals found in engine oils can also result in deterioration in catalyst performance. Lube oil phosphorus is a non-selective poison that effectively masks surface active catalyst sites, independent of the type of catalyst formulation. Generally, phosphorus deposits heavily at the front end of the catalyst brick, and typically resides mostly on the surface of the washcoat. There is some concern that phosphorus could react with other poisons and a catalyst washcoat to form phosphates that persist on the washcoat surface and mask the catalyst sites (Bunting, More, Lewis, & Toops, 2004). More research is needed here to determine the durability requirements to meet future full useful life provisions; 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 (Williams, et al., 2011; Lance, et al., 2016). Extensive testing of light-duty and heavy-duty aftertreatment systems exposed to biodiesel exhaust at the 10-ppm metal impurity specification for biodiesel has been published by NREL with funding from the National Biodiesel Board (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 (Williams, et al., 2014). 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 (Lance, et al., 2016).

The metal content of B100 from field samples analyzed by researchers at NREL (https://www.nrel.gov/docs/fy19osti/72341.pdf , https://www.nrel.gov/docs/fy13osti/57662.pdf) have shown metal content far below the current specification for the vast majority of samples collected, and the impurity level has been coming down over the sample years in 2013 and 2019. 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 (CARB, 2020). 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 standards in the Omnibus.

CARB staff also collected and analyzed over 400 diesel and biodiesel blend samples collected at retail fuel pumps throughout California in 2019 (CARB, 2020). 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 U.S. 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

In support of cost-benefit analyses conducted by CARB 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 having an architecture like System 1 in Figure 2. The costs were based on meeting today's FTP-limit of 0.2 g/bhp-hr over a useful life of 435,000 miles. The hardware included the DOC, DPF and SCR catalysts along with the DEF dosing system and OBD sensors and controllers necessary to comply with current OBD requirements. We estimated costs for two engine sizes, 6-7L and 12-13L. The former is often found in Class 4-6 heavy-duty vehicles while the latter is found in Class 7-8 vehicles.

The 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 (Posada, Isenstadt, & Badshah, 2020). 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) (Posada, Isenstadt, & Badshah, 2020). 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 (Posada, Chambliss, & Blumberg, Costs of Emission Reduction Technologies for Heavy-Duty Diesel Vehicles, 2016). It is important to note that the average price of a heavy-duty line-haul truck has historically increased by about 1% per year (Posada, Chambliss, & Blumberg, Costs of Emission Reduction Technologies for Heavy-Duty Diesel Vehicles, 2016) 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 (Posada, Isenstadt, & Badshah, 2020). 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 similar to System 3 in Figure 2. 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 are currently being demonstrated in the CARB Low-NOx demonstration program. Two cost estimates were prepared; one that assumed today's durability and warranty requirements, and one assuming longer durability and warranty requirements – 1 million mile useful life (FUL) and 800,000 mile warranty for class 8 and 550,000 mile FUL and 440,000 mile warranty for Class 4-7 starting in 2027 – that were initially proposed by CARB (CARB, 2019). Since that time, CARB staff have revised the FUL and warranty requirements to those included in the current Omnibus. Therefore, we expect the cost estimate for longer FUL and warranty provided below to represent a worst-case scenario.

For a vehicle with a 6-7L engine, the incremental hardware improvements needed to meet a 0.02 g/bhp-hr certification limit on the FTP cycle and future LLC standard at today's durability and warranty requirements were estimated to add about $1,300 to $1,800 to the cost of the engine efficiency and emission control technologies. For a Class 8 tractor with a 12-13L engine similar incremental improvements were estimated to add about $1,500 to $2,050 (less than 1.2%) to the cost of a MY 2027 truck, estimated to be approximately $177,000, based on a historical 1% annual rate of MSRP increase reported by ICCT. The estimated incremental costs to meet the above referenced durability and warranty requirements for a 6-7L engine and 12-13L engine were $1,800 to $2,450 and $2,000 to $2,750, respectively. The estimated total additional emission control cost in 2027, including a 0.02 g/bhp-hr FTP tailpipe limit, LLC limit, 1-million-mile durability requirement and 800,000 mile warranty, would be $3,100 to $4,250 for 6-7L engines and $3,550 to $4,800 for 12-13L engines. If a Class 8 truck with 12-13L engine is assumed to sell for an average price of $177,000 in 2027, based on the historical 1% annual rate of increase reported previously, the additional cost of emission controls on this truck will account for roughly 2-2.7% of the total vehicle price. It is important to reiterate that these the cost estimates are biased high since they are based on more stringent requirements than those included in the final Omnibus proposal.

MECA estimated that the proposed NOx reductions could be achieved with an approximate cost-effectiveness from $1,000 to $5,000 per ton of NOx reduced. We used a cost-effectiveness methodology that is based on both certification emission levels as well as in-use emissions reported by CARB (Hu, et al., 2019) following the 2017 Carl Moyer Guidelines (CARB, 2017), and assuming typical heavy-duty engine power, load and annual use. Benefits were calculated for a vehicle's current full useful life of 435,000 miles. The resulting range of cost-effectiveness values is due to variability in vehicle and engine characteristics. For example, replacing a higher-emitting vehicle that operates more frequently and lasts longer on the road will be more cost-effective than replacing a lower-emitting vehicle that operates for less time. U.S. EPA's estimate of $2,000 per ton NOx reduced for the 2010 heavy-duty NOx standards is within this range (40 CFR Parts 69, 80, and 86, 2001), and both are significantly below the average cost of controls on stationary power plants and industrial NOx sources, which have been reported to range from $2,000-$21,000 per ton (U.S. EPA, 2017). Similarly, CARB estimated the cost-effectiveness for future low-NOx requirements to be approximately $6,000 per ton (CARB, 2019).

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

MECA cost estimates were submitted to the survey funded by CARB and conducted by NREL to develop overall cost estimates for engines with emission controls to meet the proposed Omnibus requirements. At the time of NREL's survey, these standards included an assumption of longer warranty and durability requirements than those in the current Omnibus proposal. For example, NREL's study assumed Class 8 trucks would need to meet durability requirements of 1 million miles and warranty requirement of 800,000 miles. These have been lowered by 200,000 miles each since then. 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. Therefore, NREL and CARB acknowledge 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 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 and CARB staff.

Regulatory Flexibility

Optional 50-state program

We recognize California's unique air quality problems, and specifically, the need to reduce NOx in Southern California as early as possible in order to meet the state's ozone NAAQS goals.

We also understand that a significant contribution of the heavy-duty vehicle NOx emissions come from out-of-state trucks, which will not be required to meet California's Omnibus interim 2024-2026 requirements. Therefore, MECA supports a nationwide technology-advancing standard for heavy-duty engines. While some OEMs may choose to certify a limited number of their engines to CARB's 0.05 g/bhp-hr FTP limit and make these available in all 50-states in order to generate early compliance credits outside of California ahead of 2027, we understand CARB's motivation to provide an optional national program in the event that some OEMs may be challenged to meet CARB's proposed California interim standards in 2024. The optional 50-state-directed standards for MY 2024-2026 represents a rational approach for CARB to try to obtain air quality benefits as early as possible until U.S. EPA begins implementing the CTI (most likely) beginning with MY 2027 engines. However, we also recognize that the federal standard to be established in the CTI could be influenced by this 50-state optional standard. Therefore, MECA believes that the inclusion of this relatively weak 50-state option in 2024 reinforces the need to set the most stringent technologically feasible standards in MY 2027.

While the optional program could result in emissions benefits and provide flexibility to OEMs, we want to reiterate our position that technology is readily available today and can be integrated on trucks in the 2024 timeframe to achieve greater emission reductions than represented by the generous emission limit of 0.1 g/bhp-hr over the FTP under the proposed 50-state voluntary program. Furthermore, an emission limit of this magnitude would not prompt technology adoption to prepare the industry for a 2027 national standard of 0.02 g/bhp-hr on the FTP in 2027. As noted in CARB's April 2019 white paper, emission results submitted by OEMs on fully aged systems indicate that FTP limits between 0.05 and 0.10 g/bhp-hr are being measured on some engines and aftertreatment at today's durability requirement. Technology development continues and the catalysts provided for the first aftertreatment system on the 2014 Volvo engine at SwRI were quite different than those offered just a few years later for the 2017 Cummins X15 engine. In fact, the engines themselves are quite different and represent a variety of engine designs on trucks in the market.

New technology will likely be deployed on 2024 engines when they become available. As we discuss in our 2024 technology white paper (MECA, 2019), the combination of engine calibration, thermal management and exhaust aftertreatment technologies being offered to OEM customers today achieve FTP levels below 0.05 g/bhp-hr. During the initial calibration and aftertreatment screening work at SwRI, the stock 2014 commercial aftertreatment system could achieve less than 0.1 g/bhp-hr with only calibration improvements. In the early technology screening phase of the program, SwRI showed that some of the traditional aftertreatment designs with better catalysts and substrates, provided by MECA members, and engine based thermal management reduced the emissions down to the 0.05 g/bhp-hr level. Today, manufacturers are offering catalyst formulations to their customers for aftertreatment that delivers emissions below 0.05 g/bhp-hr on the FTP (MECA, 2019).

We recognize that the 50-state option is a voluntary pathway to certify all engines nationally at a less stringent FTP limit than CARB is proposing while also meeting a new low load certification cycle and in-use compliance program in 2024. We noted in previous discussions and comments to CARB that setting a stringent intermediate standard has the effect of incentivizing the industry (OEMs and suppliers) to work together and explore some technologies and strategies in MY 2024 that will provide experience on the path to compliance with MY 2027 standards. This opportunity to learn through a sufficiently stringent intermediate standard will help to ensure success in meeting CARB's final 2027 proposed standards. We agree that if a weaker, optional compliance path is chosen in 2024, the ability to generate federal compliance credits should be forfeited as proposed in the staff ISOR.

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 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. We are concerned however with the credit program proposed for zero-emission trucks as these will be mandated by a different regulation the Board recently adopted.

MECA supported the Advanced Clean Trucks (ACT) regulation adopted by the Board in June 2020. MECA members are supplying energy storage materials and powertrain components for the battery electric and fuel cell trucks that ACT will mandate. These technologies deliver significant GHG reductions and ultimately air quality benefits. The ACT sets sales mandates as a percentage of a manufacturers' truck sales in California for each weight class. Simultaneously, the Omnibus regulation requires significant tailpipe NOx reductions from future heavy-duty vehicles equipped with combustion engines over all real-world driving conditions. These must operate for longer useful life and comply with a more stringent compliance program and warranty requirements. The Omnibus also outlines incentives in the form of voluntary national standards for low NOx trucks and emissions credits to encourage early introduction of advanced cleaner technology vehicles. The two regulations will be implemented on the same timeline and impact the same sector of heavy-duty vehicles.

Because ZETs are mandated by the ACT rule, MECA believes that the inclusion of proposed HD-ZEV NOx credits in the Omnibus regulation for model year 2022-2030 electric trucks effectively rewards compliance with the ACT rule in the Omnibus and could result in unintended consequences of higher emitting diesel trucks operating for decades in the state. Furthermore, the HD-ZEV NOx credits can be sold and/or transferred to any HD vehicle weight class, whereas credits for HD low NOx vehicles are only provided for early compliance and can only be used within the same vehicle weight class. Therefore, the easier to electrify lighter (class 4-6) weight classes could generate significant NOx credits that manufacturers could use to offset higher emitting diesel engines at the FEL cap from the class 7-8 trucks. We calculated the number of class 7-8 diesel engines that could be built from 2027-2030 that emit NOx at 2.5 times the standard. We estimated electric truck sales from the total truck sales projections in the state from the ACT ISOR multiplied by the ACT sales requirements for years 2024-2030. We then assumed credits would be generated through 2030 and used by OEMs to meet the MY 2027 emission standard of 0.02 g/bhp-hr by averaging with diesel engines certified from MY 2027-2030 to 0.05 g/bhp-hr. As a consequence of this scenario, over 12,000 higher emitting diesel trucks with service lifetimes of 10-15 years could be sold, generating an additional 523 tons of NOx over their useful lives. This scenario assumes no additional ZEV trucks are sold beyond what is already required in ACT.

We believe that the NOx inventory impact from direct NOx credit averaging and banking is a conservative estimate because HD-ZEV 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 California in-state electricity production. We took into account California Energy Commission (CEC) renewable energy targets (44% in 2024 to 60% in 2030) and manufacturer claimed electric efficiencies from marketing materials. Transmission and charging losses were not included, nor were smart charging strategies.

HD Low NOx truck emissions were estimated using an extrapolation of the established CARB methods to find the cost-effectiveness of funding air quality projects for Congestion Mitigation and Air Quality (CMAQ) projects (https://ww2.arb.ca.gov/resources/documents/congestion-mitigation-and-air-quality-improvement-cmaq-program) and regulated tailpipe NOx standards. Upstream fuel related NOx emissions from refining of 20% were also added. Fuel economy values of 7 mpg were approximated for Class 8 trucks using U.S. DOE and industry publications for diesel vehicles. These are lower than required by future HD Phase 2 GHG regulations, which provides a conservative estimation.

On a gram-per-mile basis, a MY 2024-2026 class 8 low NOx diesel truck will emit about 0.15 g/mile, and MY 2027 and later trucks 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. For these reasons, MECA recommends that HD ZEV NOx credits issued for electric trucks under the Omnibus be limited to only the earliest years of implementation to provide flexibilities to truck manufacturers to introduce the cleanest diesel trucks in the state as early as possible while limiting potential excess NOx emissions.

Conclusion

MECA strongly supports CARB's proposed Omnibus Regulation that will result in cost effective air quality benefits for millions of Californians living in nonattainment areas and/or along highways, ports and other freight corridors. MECA believes that the emission limits and implementation timeline of the proposal are technologically achievable and cost effective. Low load testing on engine and reaction modeling has shown that thermal management technologies, current generation catalysts and close-coupled aftertreatment can achieve the proposed certification and in-use requirements under the most challenging real-world operating conditions. Our industry is prepared to do its part and deliver cost-effective and durable advanced emission control and efficiency technologies to the heavy-duty sector to assist in simultaneously achieving lower GHG and NOx emissions, while also meeting other criterial pollutant standards.

In closing, we commend the California Air Resources Board for its continuing efforts to provide the people of California with healthy air quality and for demonstrating true leadership in this innovative regulatory program that will significantly reduce PM and NOx emissions from heavy-duty on-road diesel trucks. We urge CARB to work with U.S. EPA to adopt a national set of standards that harmonize a single set of requirements. We also wish to thank CARB staff for its willingness to work closely with all interested parties and for its tireless efforts to develop effective implementation strategies. Our industry pledges its continued support and commitment to ensure that the desired emission reductions outlined in this Low NOx Omnibus regulation are effectively achieved within the time frame specified in the proposal.

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