Appendix I

Current and Advanced Emission Control Strategies
and
Key Findings of CARB/SwRI Demonstration Work

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LIST OF ACRONYMS AND ABBREVIATIONS USED IN APPENDIX I

Acronym or Abbreviation	Description
A/F	Air-Fuel
AQMD	South Coast Air Quality Management District
ASC	Ammonia Slip Catalyst
AT	Aftertreatment
BMEP	Brake Mean Effective Pressure
BTE	Brake Thermal Efficiency
CAC	Charge Air Cooler
CARB	California Air Resources Board
CDA	Cylinder Deactivation
CHEDE	Clean High-Efficiency Diesel Engine
CI	Compression Ignition
CO	Carbon Monoxide
CSF	Catalyzed Soot Filter
DEF	Diesel Exhaust Fluid
DevAged	Development Aged
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
EEVO	Early Exhaust Valve Opening
EGR	Exhaust Gas Recirculation
EHC	Electrically Heated Catalyst
EIVC	Early Intake Valve Closing
FTP	Federal Test Procedure
G/BHP-HR	Grams Per Brake Horsepower-Hour
GHG	Greenhouse Gas
HC	Hydrocarbon
HGTR	Hot Gas Transient Reactor
LEV II	Low Emission Vehicle II
LEV III	Low Emission Vehicle III
LEVO	Late Exhaust Valve Opening
LIVC	Late Intake Valve Closing
LLC	Low Load Cycle
LO-SCR, LT-SCR	Light-off SCR
MB	Mini Burner
MECA	Manufacturers of Emission Controls Association
N2O	Nitrous Oxide
NH3	Ammonia
NO	Nitric Oxide
NO2	Nitrogen Dioxide

NOx	Oxides of Nitrogen
OEM	Original Equipment Manufacturer
PAG	Program Advisory Group
PM	Particulate Matter
PNA	Passive NOx Adsorber
RMC-SET	Ramped Modal Cycle – Supplemental Emission Test
RPM	Revolutions Per Minute
SCR	Selective Catalytic Reaction
SCRF/ SDPF/ SCROF	SCR Coated on Filter
SI	Spark-Ignition
SwRI	Southwest Research Institute
TP	Tailpipe
TWC	Three-Way Catalyst
U.S. EPA	U.S. Environmental Protection Agency
VVA	Variable Valve Actuation

APPENDIX I

I. Technological Feasibility of Proposed Standards

This appendix describes currently used key heavy-duty engine emission control strategies, as well as strategies that can be used to achieve the low oxides of nitrogen (NOx) emissions standards proposed in this rulemaking action. Section A below provides an overview of the currently used emission control strategies. Section B below describes strategies for achieving lower NOx emissions than today's diesel engine systems. Section C discusses strategies for reducing NOx further from spark-ignited (SI) stoichiometric combustion engines. Section D provides a summary of key findings of the California Air Resources Board's (CARB) sponsored Southwest Research Institute (SwRI) Low NOx Demonstration program.

A. Overview of Existing Strategies

As discussed in Chapter I of this Staff Report, current heavy-duty engines are required to meet a NOx standard of 0.20 grams per brake horsepower-hour (g/bhp-hr), a particulate matter (PM) standard of 0.10 g/bhp-hr and a non-methane hydrocarbon standard of 0.14 g/bhp-hr. To meet these standards, manufacturers are utilizing both engine and aftertreatment system control strategies for both compression ignition (CI) and SI stoichiometric combustion engines. Specifically, for CI engines, manufacturers are using engine controls such as cooled exhaust gas recirculation (EGR), variable geometry turbochargers, high pressure fuel injection, and other associated electronic controls, as well as aftertreatment system controls such as diesel oxidation catalyst (DOC), diesel particulate filter (DPF), urea-based selective catalytic reduction (SCR), urea injection control, and ammonia slip catalysts (ASC). For SI engines, manufacturers are using engine controls such as EGR rate control, air-fuel ratio control, and other associated electronic controls and aftertreatment strategies such as three-way catalysts (TWC). With better air-fuel ratio controls and increased catalyst volume, manufacturers have been certifying SI engines to the optional low NOx standards of 0.02 g/bhp-hr NOx, 90 percent below current standards (see Table I-2 of the Staff Report).

Currently Used Key NOx Emission Control Strategies

1. <u>Cooled EGR</u>

EGR involves routing some portion of the exhaust gas back into the engine's combustion chamber. The exhaust gas dilutes the oxygen fraction of the inlet charge entering the combustion chamber and reduces the peak combustion temperatures, thereby reducing the formation of NOx. The use of EGR to reduce NOx emissions can increase fuel consumption and PM emissions. However, manufacturers have been mitigating these negative impacts through advances in engine electronic controls, increased fuel injection pressure, and increased intake manifold boost pressure. Cooling the EGR exhaust in a heat exchanger before mixing it with the intake air stream reduces the charge air temperature resulting in lower peak combustion temperatures as well as allowing a higher density of cooled EGR to be used. The lower peak combustion temperatures and the higher density of the cooled EGR (which allows a higher fraction of EGR to be used) result in improved in-cylinder NOx emission reductions. EGR controls are also used in SI engines to reduce NOx emissions, inhibit knock, reduce pumping losses, and improve efficiency.

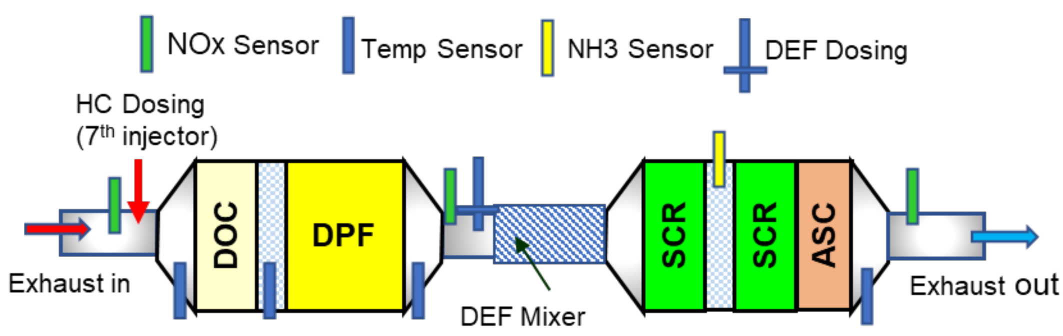
2. *Turbocharger Control*

The turbocharger consists of a turbine and a compressor coupled on a common shaft. Driven by the waste heat in the exhaust, the turbocharger compresses and increases the density of the intake air before it enters the combustion chamber. The extra compressed air forced into the combustion chamber with proportionally more fuel improves the engine efficiency and provides more power without the need to increase engine size. However, compressing the intake air also raises its temperature, which partly offsets the benefits of increasing the intake air pressure. To obtain increased boost with minimum increase in temperature, a charge air cooler is used to cool the pressurized air resulting in a high density charge and enabling more fuel to be used to deliver more power than a naturally aspirated diesel engine. Variable geometry turbochargers provide additional benefits by maximizing control of the boost pressure over a wide range of engine operations to provide better transient response, improved fuel economy, enhanced compression brake capabilities, and improve EGR control to further reduce emissions.

3. *Exhaust Aftertreatment System*

The CI engine aftertreatment system typically consists of a DOC, catalyzed DPF, SCR, and ASC to clean up the engine exhaust gases (see Figure 1). DOCs use precious metals such as palladium and platinum to promote oxidation of hydrocarbons (HC) and carbon monoxide (CO), to either reduce these pollutant emissions from the engine or to promote exothermic heat used for DPF regeneration and to oxidize nitric oxide (NO) to nitrogen dioxide (NO2). NO2 is used to promote passive soot DPF regeneration as well as to promote faster SCR catalytic reactions to reduce NOx.

Figure 1. Currently Used Diesel Exhaust Aftertreatment System



The DPF is commonly a wall-flow ceramic honeycomb monolith filter coated with precious metals such as palladium and platinum. The DPF traps soot as the exhaust passes through the filter walls. The collected soot is then burned or cleaned up in a process called DPF regeneration which can be done actively or passively, depending on the amount of NO2 present in the DPF and the temperature of the exhaust gas. NO2 used in this process is formed in the DOC as well as in the catalyzed DPF by oxidizing NO to NO2 in the exhaust. Passive regeneration takes place continuously at exhaust temperatures around 250°C to 350°C in the presence of a sufficient amount of NO2, which oxidizes the soot to form carbon dioxide (CO2). Active regeneration is initiated by engine controls based on exhaust system backpressure caused by soot build-up in the DPF. During active regeneration, heat is typically added to the exhaust stream using a fuel burner or by injecting fuel over the DOC (HC doser or through post-injection) to increase the exhaust temperature to above 550°C to burn off soot build up. Ash is also present in the soot and cannot be burned off. Ash is collected in the DPF and periodically needs to be cleaned out during set maintenance intervals using a specialized cleaning process. The minimum ash removal interval allowed by CARB and U.S. Environmental Protection Agency (U.S. EPA) on-road heavy-duty regulations is 150,000 miles.

To meet the current heavy-duty engine NOx standards, manufacturers are currently using SCR systems that utilize ammonia as the reductant from a urea-based diesel exhaust fluid (DEF). In the SCR system, DEF is injected into the hot exhaust stream to break down the NOx into simple nitrogen and water. For on-road heavy-duty vehicles, the most commonly used SCR catalysts are copper and iron zeolites and vanadia. Copper zeolite exhibits an excellent low temperature activity (150°C - 450°C) but is susceptible to sulfur contamination and requires occasional high temperature desulfation. Iron zeolite has better high temperature performance (350°C - 600°C) and is less affected by sulfur contamination reducing the need for high temperature desulfation but is susceptible to moderate HC poisoning. It also requires better NO2 management in the exhaust gas to achieve needed low temperature NOx control performance. Vanadia operates best in the temperature window between 300°C to 450°C but has poor durability at higher exhaust temperatures (550°C to 600°C), and thus cannot be utilized in systems that require active DPF regeneration (which occurs around 650°C). Similar to iron zeolites, its low temperature performance strongly depends on NO2 availability in the exhaust. Vanadia-based catalysts are not currently used for on-road applications in North America due to the possibility of toxic emissions of vanadia compounds being produced at elevated exhaust gas temperatures that may occur during active DPF regeneration.

Current SCR systems provide high NOx conversion efficiencies during steady-state and high-speed operations where exhaust temperatures are high enough for the SCR system to function effectively. Despite meeting the current standards during certification test cycles, they have poor NOx conversion efficiency when exhaust gas temperatures are low, such as during cold start, low-speed, low-load driving and during extended idling. This is because SCR performance is limited by urea decomposition issues at exhaust gas temperatures below 180°C. If urea is injected at exhaust gas temperatures below 180°C, solid deposits of ammonium nitrate can form over the catalyst and exhaust system, resulting in degradation in SCR conversion efficiency and catalyst damage. As a result, SCR systems are not operated at low exhaust temperatures that prevail during low load operations. Unfortunately, these low load conditions dominate actual operation of heavy-duty vehicles in urban stop-and-go operation in communities and on congested freeways where the reduction of NOx is most needed.

SI natural gas engines use a TWC to control NO_X, CO, and HC, without the need of a DPF to meet PM standards. A TWC uses precious metals such as platinum, palladium, and rhodium to simultaneously oxidize HC and CO and reduce NOx. Catalytic conversion efficiency depends highly on the precious metal formulation of the catalyst. In addition, a necessary condition for high conversion efficiency of the three pollutants is that the engine operates in a narrow range of air/fuel ratios close to stoichiometric. An oxygen sensor in the exhaust is used to detect the presence of free oxygen in the exhaust gas to determine whether the engine is operating on the lean or rich side of stoichiometry. The sensor then sends a signal to the electronic control unit to adjust fuel injection rate so that the engine operates in a narrow window around the stoichiometric set point.

B. Low NOx Emission Control Strategies

There are two main approaches for reducing emissions further at the tailpipe: engine controls and aftertreatment system controls. Engine control strategies comprise software and hardware-based controls designed to achieve more efficient combustion and reduced engine-out emissions as well as enable improved thermal management of the exhaust stream for more effective aftertreatment system performance over a wide range of the vehicle operations. For CI engines, exhaust aftertreatment system control strategies include improvements to the catalyst formulations, urea injection controls, exhaust system thermal insulation, supplemental heat addition to the exhaust, and placement of the aftertreatment system close to the engine. It is not expected that a single strategy or technology would enable NOx emission reductions necessary to achieve the levels of the proposed NOx standards. However, adequate NOx emission reductions to meet the proposed standards can be realized from improved integration of engine controls with advanced aftertreatment system control strategies.

The following is a brief description of technologies and strategies that could be implemented to further reduce NOx emissions at the tailpipe. Some of the engine control strategies and supplemental energy sources designed to add heat to the exhaust may require additional fuel consumption during cold starts or low temperature operations. However, the integration and calibration of these technologies is expected to achieve significant NOx reductions with minimal or no impact on greenhouse gas (GHG) emissions over the vehicle's entire duty cycle. In some cases, the selection of certain engine technologies like cylinder deactivation (CDA) can achieve desired NOx emission reductions while also reducing GHG emissions (which would help meet existing Phase 2 GHG requirements). For SI stoichiometric combustion engines, emission control strategies are less complex but can significantly reduce NOx emissions with improved TWC formations and advanced air-fuel ratio controls.

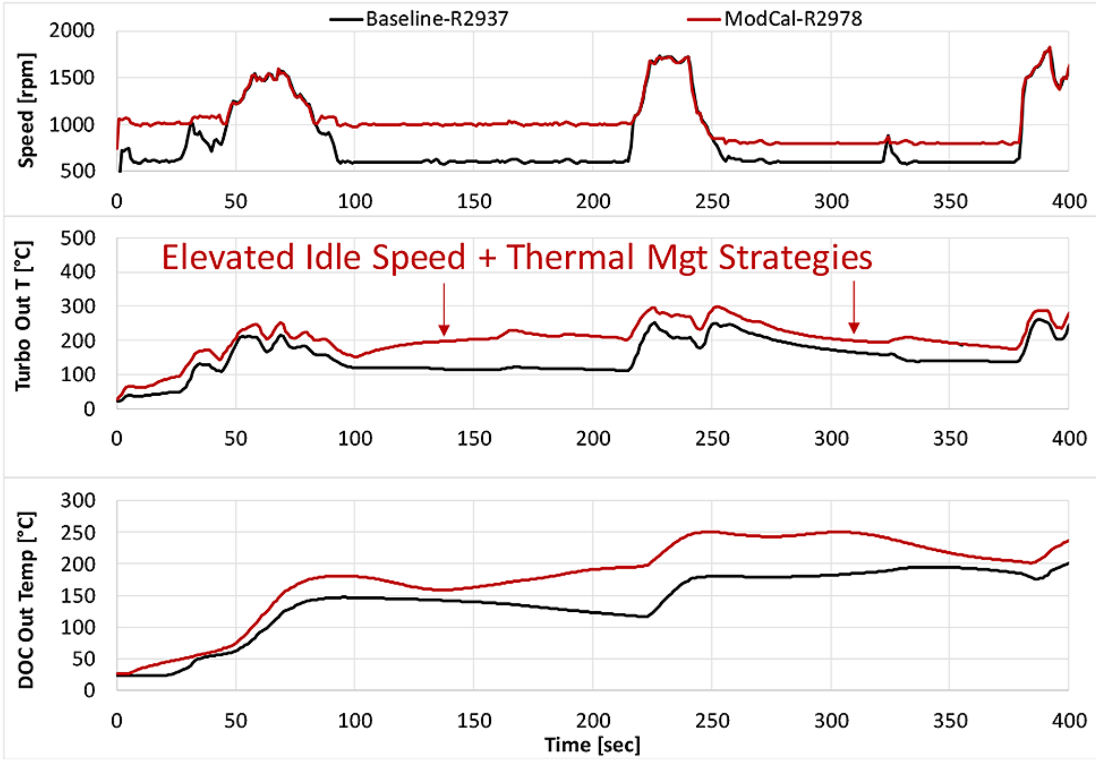
1. *Engine Calibration Strategies*

Engine calibration strategies such as increased idle speed, increased EGR rates, intake and exhaust throttling, and multiple fuel injection can also be used to increase the exhaust temperature and accelerate aftertreatment warm-up and reduce engine-out NOx during cold start conditions. When used in conjunction with advanced aftertreatment systems, these strategies can be used to achieve NOx emissions levels below 0.05 g/bhp-hr at the tailpipe. These strategies have been demonstrated by SwRI in Stages 1, 2, and 3 Low NOx test programs to achieve low levels of tailpipe NOx on existing diesel regulatory cycles and a newly developed low load cycle (LLC).

In the SwRI Stage 1 Low NOx test program, engine calibration that included increased idle speed, double post fuel injection, and increased EGR rates together with a stock aftertreatment system, were able to achieve NOx levels of approximately 36 percent below baseline on the Federal Test Procedure (FTP) cycle with a corresponding GHG penalty of about 0.4 percent (Sharp et al., 2017b). In the same program, with advanced aftertreatment systems that included a passive NOx adsorber (PNA), a fuel burner, SCR on DPF, a downstream SCR, and ASC, NOx emissions were reduced on the FTP and the Ramped Modal Cycle - Supplemental Emission Test (RMC-SET) down to 0.016 and 0.02 g/bhp-hr, respectively, using development-aged parts exposed to thermal degradation of the aftertreatment system at useful life. The thermal and chemically aged aftertreatment system had FTP and RMC-SET emissions of 0.036 and 0.038 g/bhp-hr, respectively.

In conjunction with advanced engine hardware and aftertreatment systems, modified cold calibration strategies are also being used in the SwRI Stage 3 Low NOx program to demonstrate significantly lower NOx emissions on the regulatory cycles as well as the LLC. The modified calibration includes increased EGR rates, multiple injections, and elevated idle speed. The strategy was employed during the first 475 seconds of the cold FTP after which the calibration was switched to fuel economy calibration mode. From Figure 2, it is clear that the strategy provides significant increases in exhaust temperatures enabling rapid aftertreatment warm-up. Using the modified cold calibration, the time to reach a 150°C DOC outlet temperature was reduced from 233 to 70 seconds and the cumulative engine-out NOx was reduced from 6.3 to 2.0 grams. However, CO2 emissions on the composite FTP increased by 0.5 percent, and increases in HC emissions were also observed (Neely et al, 2020a).

Figure 2. Cold FTP Results with Baseline and Modified Calibration



2. Bypasses: Turbocharger / EGR cooler/ Charge Air Cooler

The EGR and charge air cooler bypasses allow hot EGR and uncooled charge air to be routed from the intake manifold into the exhaust chamber during certain operating conditions. The higher inlet charge temperature improves fuel atomization and air-fuel mixing during the ignition delay period and during combustion, increasing exhaust temperatures. A turbocharger bypass allows the exhaust to remain hot at the SCR by avoiding a heat loss across the turbine walls. The use of these strategies would be effective under certain engine operating conditions such as during cold start, extended idle, and light load operations.

These hardware strategies were screened by SwRI in the Stage 3 Low NOx program to evaluate their potential to increase exhaust temperatures and their impacts on engine-out NOx and CO2 emissions (Neely et al, 2020a). Among the hardware options evaluated, SwRI investigated exhaust thermal management using EGR cooler bypass (bypassing 50 percent of the EGR and completely or 100 percent of the EGR), charge air cooler (CAC) bypass and turbine bypass. Under steady state tests of 1000 revolutions per minute (rpm) and 2.5 bar brake mean effective pressure (BMEP), a 100 percent EGR cooler bypass provided a temperature increase of 100°C without any additional fuel penalty but with only a small engine-out NOx impact and soot mass increase. In addition, HC emissions were also reduced due to increased intake manifold temperature. Bypassing the CAC in addition to 100 percent of the EGR cooler bypass provided another 18°C increase in exhaust temperatures with some soot increase. For the same test condition, a 50 percent EGR cooler bypass provided approximately 30°C increase in exhaust temperature with slight soot mass reduction. The turbine bypass, resulted in approximately 60°C increase in exhaust temperature with a NOx and exhaust energy decrease, a small fuel consumption increase, and a slight soot mass reduction.

To conduct the steady state test for the 100 percent EGR cooler bypass, certain components had to be removed to allow testing due to exceeding temperature limits. Thus, it was not selected for final demonstration since transient EGR control by the stock engine control module was not possible without the removed components. However, the results demonstrate the potential for increasing exhaust gas temperatures of completely bypassing the EGR cooler.

3. Supplemental Heat Addition

There are several active thermal management approaches for adding heat to the exhaust:

(i) Direct heat addition to the exhaust by dosing fuel directly into the exhaust or through post injection, and oxidizing it over the oxidation catalyst or by combusting the fuel in a fuel burner with the flame entering the exhaust system. Using a fuel burner or direct in-exhaust fuel dosing for heat addition typically negatively impacts GHG emissions.

(ii) Use of an "electrically heated catalyst" upstream of the main catalyst to deliver heat directly to the exhaust gases. The electrical energy needed is generated by the engine's alternator and therefore is a parasitic load on the engine, consuming fuel. However, the GHG penalty can be reduced or eliminated when used in combination with electric hybrid vehicles where the electrical energy used for heating exhaust is recovered via braking energy.

(iii) Direct heat addition to the DEF to vaporize it to form ammonia and directly dose the heated DEF into the exhaust ("Heated DEF Dosing") at low exhaust temperatures as low as 130°C. In this strategy the heat can be generated using an electrical heater or alternatively use heat from the exhaust by taking partial exhaust flow from the main exhaust upstream of the turbocharger, heating the urea solution to form ammonia.

The above three strategies were evaluated in the SwRI Stages 1 and 2 Low NOx testing programs (Sharp et al., 2017b). The fuel burner (or mini burner) system was selected and used for the final demonstration of the SwRI Stage 1 Low NOx testing program.

4. Passive NOx Adsorber

A PNA is a NOx storage device that is placed upstream of an SCR to store NOx during cold start and during low temperature operations and then release the NOx at higher temperatures when the downstream SCR catalyst becomes active. A PNA can combine the functions of a DOC as well as NOx storage device. A PNA was one of the aftertreatment technologies used to demonstrate the feasibility of low NOx emissions in the SwRI Stages 1 and 2 Low NOx test programs. PNAs are effective in reducing cold start emissions. However, they are sensitive to sulfur contamination which reduces their adsorption capabilities and requires frequent desulfation at higher exhaust temperatures to recapture NOx adsorption performance.

5. Advanced SCR Systems

SCR catalyst formulations and designs have been undergoing continuous development to improve the durability and the overall NOx conversion performance. To improve the temperature operating window, catalysts with high cell density and thinner, durable, substrate walls are being developed. The high cell density and increased porosity provide increased surface area to allow sufficient contact area between the exhaust gas and the active catalytic materials. The thin substrate walls also reduce the catalyst thermal mass allowing for more rapid warm-up. Advances in SCR aftertreatment have improved catalyst efficiency and have widened the operating temperature range available for NOx control. Other catalyst formulations such as combined-SCR systems consisting of both iron and copper catalysts benefit from the characteristics of both copper and iron, allowing improved NOx reduction over a wider range of operating temperatures (Nishiyama et al., 2015). SCR NOx reduction efficiencies have been observed to have increased to 90 percent or more at temperatures down to 200°C (Newman, 2018). Over the years, development of higher efficiency catalysts, improved DEF mixing, and packaging designs have resulted in overall system downsizing and cost savings (MECA, 2019).

6. SCR on DPF

SCR on DPF technology (also referred to, by different manufacturers as SCRF, SDPF, or SCRoF) is an integrated NOx-PM aftertreatment technology where the SCR catalytic material is coated in the porous walls of the DPF substrate. It combines the functionalities of both the DPF and the SCR into one aftertreatment component, thereby reducing system size, weight, thermal mass, complexity, and cost. With the addition of a compact urea mixer, the system can be close-coupled to the DOC for faster light-off and improved cold start emissions performance. To maximize NOx conversion, the system may be coupled with a separate SCR system downstream of the combined system. Copper and iron-based catalysts are more appropriate for use as SCR catalysts on the DPF due to their higher thermal stability.

SCR on DPF was one of the technology options evaluated in the SwRI Stages 1 and 2 Low NOx testing programs (Sharp et al., 2017b; Sharp, 2020b). In combination with other strategies such as engine thermal management strategies (discussed above) and advanced aftertreatment systems that included a PNA, a fuel burner to provide supplement heat to the exhaust, and a downstream SCR catalyst, the system achieved extremely low NOx levels on the regulatory cycles and the LLC.

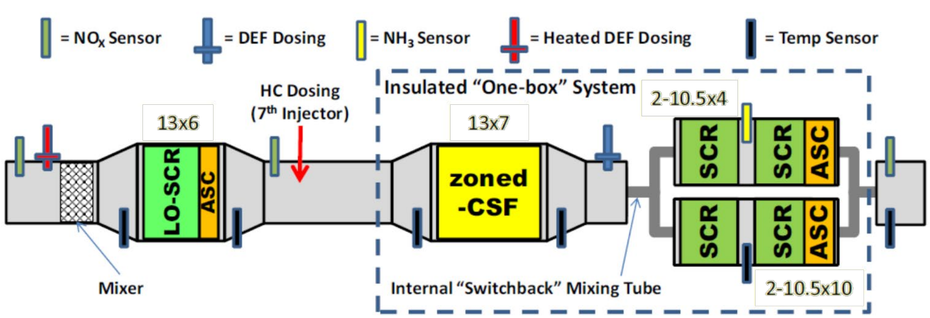
7. *Dual SCR with Dual Dosing*

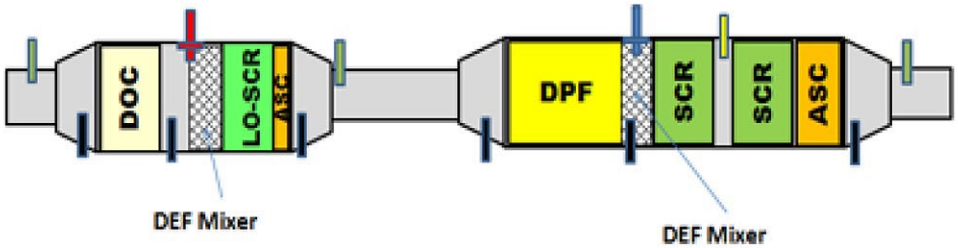
Dual SCR systems consists of two SCR systems arranged in series, each with its own DEF dosing system. There are several configurations of these systems. The upstream SCR catalyst, referred to as a "light-off SCR," could be located close to the engine's turbocharger, either upstream of the DOC or just downstream of a close-coupled DOC and underfloor, but upstream of the DPF. Placing it close to the turbocharger upstream of the DOC enables the light-off SCR to take advantage of passive thermal management, using hotter engine exhaust temperature and less thermal mass between the two components to effectively reduce NOx during cold start and low load operations, until the downstream SCR temperature reaches its ideal operating state for maximum NOx control. A zone coated ASC downstream of the light-off SCR is also typically needed to clean-up any ammonia-slip and prevent ammonia oxidation to form NOx and nitrous oxide (N2O) over the DOC and the catalyzed DPF. In addition, NOx conversion over the light-off SCR must also balance the need for NO2 for passive DPF regeneration.

The downstream SCR is typically located in the underbody of the vehicle. The downstream aftertreatment systems typically include the downstream SCR, the DPF, and the ASC that can be packaged together in a one-box system or in a traditional configuration as shown in Figure 3. The zoned-coated catalyzed soot filter (CSF) combines the functionalities of the DOC and DPF into one component, thereby reducing system size and providing better thermal management to the downstream SCR.

Promising results have been achieved by technology developers, manufacturers, and research institutions currently investigating the potential of the dual SCR aftertreatment architecture to meet very low NOx emission levels. The SwRI Stage 3 Low NOx testing program is currently demonstrating low NOx emissions using dual SCR catalysts with dual dosing and other advanced engine calibration and hardware strategies (Zavala et al., 2020). Results are shown in the summary of SwRI results discussed in section D, below.

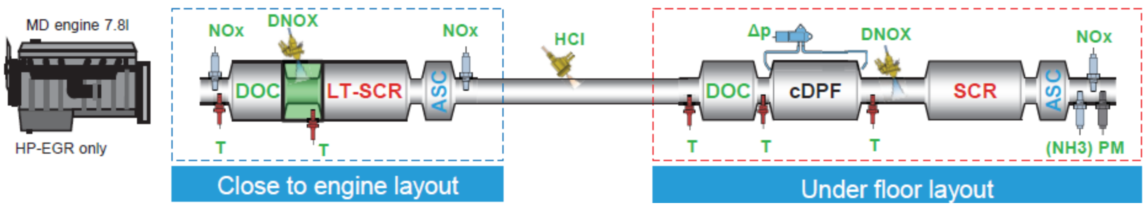
Figure 3. Close-coupled Light-Off SCR Configurations





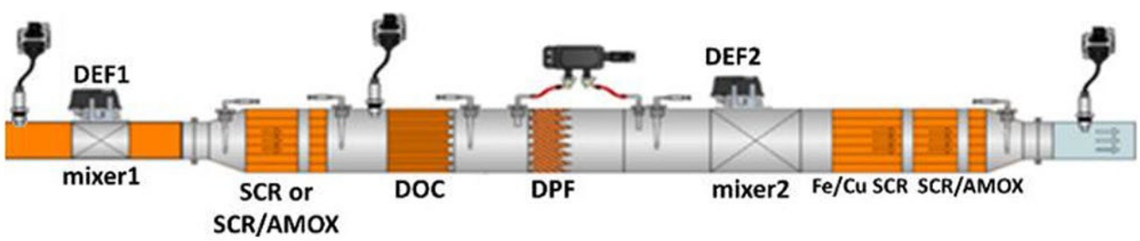
Testing by Bosch of a 7.8 liter medium-duty engine targeting NOx levels below 0.05 g/bhp-hr demonstrated composite FTP NOx levels of 0.023 g/bhp-hr using engine calibration methods and a dual SCR system with a close-coupled DOC and light-off SCR (LT-SCR) as shown in Figure 4 (Freitag, 2019).

Figure 4. Bosch Concept SCR System for Low-NOx Heavy-Duty Diesel Engines (Denoxtronic 8 SCR System)



Adelman et al. also reported the benefits of placing a light-off SCR upstream of the DOC on a 2019 model year 12.4-liter “stock” A26 Navistar diesel engine (Figure 5). Targeting emissions below 0.05 g/bhp-hr tailpipe NOx, this test program demonstrated composite FTP NOx of 0.04 g/bhp-hr with SCR conversion efficiencies of 96.9 percent on the cold FTP and 99.7 percent on the hot FTP (Adelman et al., 2020).

Figure 5. “Ultra-Low TP NOx” Aftertreatment Configuration (Adelman et al., 2020)



The results by both Bosch and Adelman et al. were achieved without using any of the engine hardware thermal management strategies such as CDA, variable valve actuation, EGR cooler bypass, etc. These results indicate that NOx emission levels significantly lower than 0.02 g/bhp-hr are feasible with additional thermal management strategies such as engine calibration and hardware strategies, or heated DEF dosing.

8. *Exhaust System Heat Retention*

Reducing the mass of the exhaust system and insulating it from the outlet of the turbocharger to the inlet of the SCR system would also reduce the amount of heat lost to the exhaust system's walls. Double walled manifolds and pipes with a very thin inner wall and an air gap separating the inner and outer wall may be used to insulate the exhaust system and reduce the thermal mass, minimizing the amount of heat lost. This technology is prevalent in gasoline-fueled engine applications and can be applied to diesel engine applications. As shown in Figure 6, packaging the aftertreatment system in a one-box system could also be used to reduce overall aftertreatment size and reduce weight, and keep the aftertreatment system warm over longer periods of time (i.e., as in a "penguin huddle").

Figure 6. Downstream Aftertreatment Configuration - One Box System

9. *Urea Injection Control*

The objective of a urea injection control system is to simultaneously minimize tailpipe NOx and ammonia emissions by enabling the urea dosing system to inject the precise amount of urea necessary for NOx conversion. Providing high precision controls is a requirement for reaching FTP NOx levels of 0.020 g/bhp-hr consistently and over multiple exhaust conditions. Model-based feed-forward and feedback (Closed-loop) DEF dosing controls with appropriate exhaust sensors are necessary in applications, where high NOx conversion efficiency is needed. For a closed-loop SCR control system, a NOx sensor upstream and downstream of the SCR and mid-bed ammonia sensors are needed to monitor the amount of ammonia coverage on the SCR catalyst and adjust the amount of urea injected to reach the coverage design target.

10. *Ammonia Slip Catalyst*

An ASC is a precious metal-based oxidation catalyst that is used to oxidize excess unreacted ammonia that may have slipped through the SCR catalyst and would otherwise be exhausted to the environment. ASCs are designed to have high selectivity for ammonia, oxidizing ammonia to form nitrogen. However, if the NO to ammonia ratio coming out of the SCR catalyst is very high, the catalyst may also catalyze undesirable reactions that produce N2O, a potent GHG, or oxidize the ammonia to produce NOx at the tailpipe. Thus, careful DEF injection strategies along with improved ASC designs are being developed to maximize ammonia storage on the SCR while avoiding the generation of N2O or the oxidation of that ammonia slip into tailpipe NOx. The latest generations of ASC with reduced precious metal content are showing much better selectivity for ammonia, while forming lesser undesirable products at the tailpipe.

11. Cylinder Deactivation

Among the many engine hardware technologies (EGR cooler bypass, charge air cooler bypass, turbine bypass, SuperTurbo, and air gap insulated exhaust manifold) evaluated by the SwRI Stage 3 Low NOx program, CDA ranked the highest for providing significant CO2 reductions while also providing significant increases in exhaust temperatures during the cold FTP test (Neely et al, 2020a).

CDA involves selectively shutting down one or more cylinders by cutting fuel injection as well as deactivating the intake and exhaust valves of the selected cylinders. The air trapped inside the deactivated cylinders is compressed and then pushes back the piston, effectively acting like a "spring." CDA in diesel engines provides improved fuel efficiency through reduced pumping losses and friction as well as increased exhaust gas temperatures for faster warm-up and to keep warm the exhaust aftertreatment system during idle and sustained low load operation for effective SCR operation.

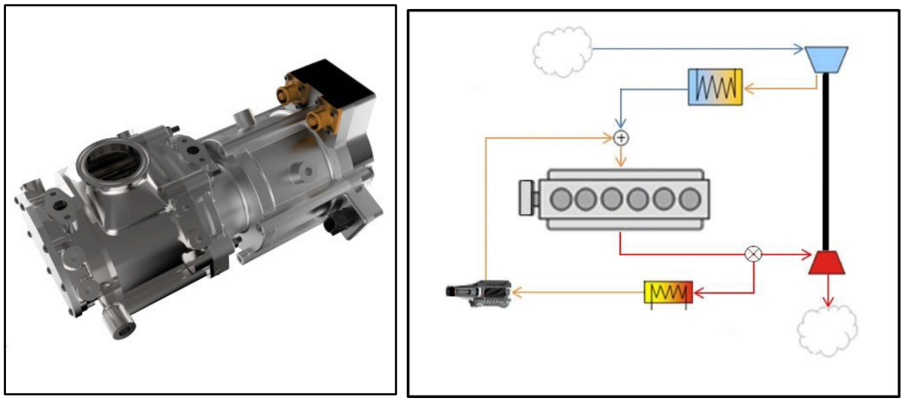
CDA is currently being investigated and developed by various manufacturers and technology developers as a technology pathway to meet the proposed low NOx standards. Singh et al. reported results of CDA tests conducted on a Class 8, 13L, 6-cylinder, Navistar engine on a number of vocational duty cycles including among others the LLC, the New York Bus Cycle, Orange County Transit Authority Cycle, and the FTP (Matheaus et al., 2020). Testing on the LLC showed an increase in SCR inlet temperature by 38°C, which allowed the SCR NOx conversion efficiency to increase from 74 percent (baseline) to 95 percent with CDA. The tailpipe NOx and CO2 were reduced by 77 percent and 12 percent, respectively.

Furthermore, another study by SwRI and Eaton demonstrated that a "stay warm" CDA strategy increased exhaust temperatures of up to 200°C while simultaneously reducing fuel consumption between 5 and 40 percent, depending on the engine operating speed and load (Morris et al, 2020).

12. EGR Pump

EGR pumps provide more precise EGR flow rates independent of the engine speed via a positive displacement pump while allowing the use of high efficiency fixed geometry wastegate turbochargers (Park et al, 2019) (See Figure 7). Driven by a 48-volt electric motor, the EGR pump allows a high volume of EGR to be pumped to dilute the intake charge air mixture with low pumping losses - improving fuel efficiency while also lowering peak combustion temperatures - reducing engine-out NOx. The EGR pump enables EGR flow where it was previously difficult or not possible to drive the flow without losses such as during low speed and transient operations and provides more accurate EGR flow rate control for better combustion and emissions management.

Figure 7. EGR Pump (source: Eaton)



13. <u>Variable Valve Actuation</u>

Variable valve actuation (VVA) involves changing the timing of closing and opening the intake or exhaust valves to improve combustion efficiency while also providing improved thermal management of the exhaust during different engine operating conditions. There are multiple VVA solutions including early exhaust valve opening (EEVO), late exhaust valve opening (LEVO), early intake valve closing (EIVC), and late intake valve closing (LIVC). VVAs are effective strategies for increasing exhaust temperatures at different engine operating conditions.

For example, EEVO of about 90° earlier than nominal was shown to increase exhaust temperatures by 30 to 80°C at different engine operating conditions including idle, low load cruise, and high load cruise conditions (McCarthy et al, 2017). The strategy resulted in a fuel consumption penalty of approximately 13 percent at high load cruise, 18 to 21 percent at low load cruise, and 22 percent at idle. The same study reported, at 1200 rpm and 2.5 bar BMEP, EIVC and LIVC were shown to increase the turbine-out exhaust temperature from about 200°C to 255°C° and 244°C, respectively. For the same engine operating condition, EIVC improved brake-thermal-efficiency (BTE) by approximately 4 percent while LIVC improved BTE by approximately 3 percent.

Furthermore, another study demonstrated how increased idle speeds and exhaust valve opening actuation, individually or combined, can be used to significantly increase the ‘‘warm-up’’ rate of an aftertreatment system without emitting higher engine-out NOx or PM, compared to a high idle thermal calibration strategy (Vos et al., 2019). The study demonstrated that increased idle speeds together with EEVO increased the engine-out exhaust gas temperature by 50°C relative to conventional idle operation and LEVO increased the engine-out exhaust gas temperature by 91°C relative to conventional idle operation.

14. <u>SuperTurbo</u>

A SuperTurbo is a device that is capable of supercharging, turbocharging, and turbocompounding. The turbine shaft is linked to the engine's crankshaft through a mechanical transmission to enable power transfer between the turbine and the engine. During transient operation, it acts like a supercharger drawing power direct from the engine for improved transient response. When the engine operates at high power, it can act as a turbocharger by taking advantage of the exhaust energy to compress intake air and thereby improve overall engine performance and efficiency. And finally, for turbocompounding, it can utilize the excess exhaust energy above that needed to drive the compressor and providing surplus power to the engine crankshaft, thus improving fuel efficiency. SwRI was able to demonstrate through limited testing that this technology can provide significant thermal management improvements during the cold start FTP. It was also shown that this device can achieve reduced GHG emissions under a broad range of engine operations (Neely et al, 2020a).

15. <u>Ducted Fuel Injection</u>

Ducted fuel injection is a relatively new fuel spray method that mimics the Bunsen burner with the potential to reduce PM emissions and improve thermal efficiency of heavy-duty diesel engines (Nilsen et al, 2018). It involves injecting fuel along the axis of one or more small cylindrical ducts within the combustion chamber, to enhance the mixture in the autoignition zone relative to a conventional free-spray configuration (i.e., a fuel spray that is not surrounded by a duct). The technology has the potential to reduce PM and NOx simultaneously, breaking the NOx / PM trade-off issue with CI engines.

16. <u>Achates Engine</u>

The Achates engine is an opposed piston engine currently under development by Achates Power. The opposed piston engine is expected to significantly reduce tailpipe NOx emissions while improving fuel economy and will reportedly cost less compared to a four-stroke CI or SI engine of similar power (Achates, 2020a; Achates, 2020b).

C. Strategies for SI Stoichiometric Combustion Engines

As mentioned above, TWCs use precious metals such as platinum, palladium, and rhodium to simultaneously oxidize CO and HC, and reduce NOx emissions. Because of their application in gasoline light-duty vehicles to meet the low emission vehicle (LEV II and LEV III) standards, TWCs have continued to improve in terms of their performance and durability since they were first introduced in 1975. Specifically, improvements have been made relative to catalyst formulation, substrate design, oxygen storage material, and exhaust thermal management. However, their application in SI heavy-duty engines is not as optimized as it is in light-duty vehicles, particularly when controlling emissions during cold start and other certain operating conditions. Thus, lessons learned from gasoline light-duty applications can also be applied to SI heavy-duty engines to improve performance. Improvements may include:

i. *<u>Substrate design</u>*: Higher cell density and thinner wall design can provide increased geometric surface area per unit TWC volume for effective catalyst distribution, small flow channels for fast heat transfer, and reduced substrate thermal mass for faster heat up during cold starts.

ii. *High oxygen storage material*: High oxygen storage capacity is critical for maintaining high catalytic conversion. The latest generation of ceria zirconia added to the washcoat of TWCs provide higher thermally stable oxygen storage capacity and allows a broader window of catalytic operation, improves catalyst light-off, and enables significant reductions of NOx emissions (Damma et al, 2018).

iii. *Close-coupled catalyst*: A close-coupled catalyst minimizes exhaust system heat losses and accelerates catalyst light-off, without negatively impacting fuel economy. Close-coupled catalysts use a palladium-only or a palladium and rhodium formulation for higher HC removal efficiency and faster catalyst light-off.

iii. *Passive heat retention*: Insulating the exhaust manifold, exhaust pipeline, and TWC increases the efficiency of transferring heat generated from the engine to the catalyst with minimum heat loss, so that the transferred heat accelerates catalyst light-off at cold start and maintains high catalytic conversion efficiency.

v. *Advanced air/fuel (A/F) ratio controls*: Because a TWC operates within a very narrow window of A/F ratio, maintaining accurate A/F ratio in cylinders is critical to achieving maximum catalytic conversion efficiency. Maintaining accurate A/F ratio control allows for better fuel economy, lower NOx emissions, and better engine performance. A zirconia-based wideband oxygen sensor widely used in gasoline passenger cars could be used for SI heavy-duty engines for accurate A/F ratio control.

One of the tasks in the SwRI Stage 1 Low NOx testing program was to demonstrate a 0.02 g/bhp-hr NOx level on the FTP and RMC-SET on a 12-liter natural gas engine. With an engine calibration that included precise A/F ratio control during transient operation, precise EGR flow and electronically controlled wastegate to precisely control boost pressure at steady state and during transient operations, and advanced close-coupled and underfloor catalysts, SwRI testing achieved 0.01 g/bhp-hr NOx on the FTP and 0.0006 g/bhp-hr NOx on the RMC-SET. Furthermore, as shown in Table I-2 of the Staff Report, manufacturers have been certifying SI heavy-duty engines to the most stringent of the existing optional low NOx standards of 0.02 g/bhp-hr NOx on the FTP and RMC-SET using improved A/F ratio controls and larger and/or improved TWCs.

D. Summary of CARB SwRI Demonstration Work

CARB contracted with SwRI to demonstrate strategies and technologies capable of meeting much lower NOx emission standards, with a goal for the project to demonstrate an aftertreatment system that could meet a NOx standard of 0.020 g/bhp-hr. The SwRI work was performed under three separate contracts and subcontracts referred to as Stage 1 (and subcontract 1b), Stage 2, and Stage 3 (and subcontract 3b). It should be noted that this work was also supported with several partners, such as the

Manufacturers of Emission Controls Association (MECA), U.S. EPA, South Coast Air Quality Management District (AQMD), Volvo, Cummins, Eaton, Clean High-Efficiency Diesel Engine (CHEDE) Consortium, and the Port of Los Angeles. This effort aimed to assess the technical capability to achieve significant NOx reductions using the most up-to-date production engine platforms available, augmented by production-intent aftertreatment components and other bolt-on parts, and engine calibration improvements able to assist the operation of the aftertreatment system.

The Stage 1 contract evaluated both a natural gas-fueled stoichiometric and a diesel-fueled heavy-duty engine. During the finalization of the SwRI Stage 1 program, a natural gas-fueled heavy-duty engine was certified to California's optional 0.02 g/bhp-hr NOx standards, so the remaining demonstration work shifted to focus on the diesel-fueled heavy-duty engine. Since that time, several more stoichiometric heavy-duty engines have since been certified to 0.02 g/bhp-hr NOx standards, both natural gas and propane fueled engines.

The following are the two heavy-heavy diesel engines used by SwRI:

- 2014 Volvo MD13TC diesel-fueled engine (Stages 1 and 2)
- 2017 Cummins X15 diesel-fueled engine (Stage 3)

The technologies examined in detail and ultimately chosen for the program were practically constrained by each potential technology's readiness (i.e., the potential for near-term commercial production applicability) and implementation complexity relative to the project's external budget and timeline constraints. The breadth of technologies included were greatly aided by original equipment manufacturers (OEM), supplier in-kind support through MECA and its members, and the SwRI CHEDE Consortium enabling inclusion of advanced aftertreatment components and systems as well as engine modifications on the second engine platform. Further support came from U.S. EPA, AQMD, and the Port of Long Beach.

These projects were intended to illustrate the scale of reductions achievable from available, production-intent components. However, they were not intended to be a full commercialization exercise, and CARB staff recognizes that certain platform-specific validation work typical of any commercialization process will be needed for each engine brought to market. Examples include application engineering activities matching the product to its final use such as the detailed final calibration of regeneration strategies and certain long-term trim adjustments in the control system dealing with the interactions of the specific strategies programmed onto the electronic engine control unit with the selected hardware across the application duty cycles.

While a significant number of technologies had some level of documented research, modeling, bench testing, or engine testing evaluation, there are some strategies and technologies in development that have not been fully examined, but have potential to provide significant NOx and GHG control improvements. Examples of potential technologies include changes to the combustion chamber, rotating assembly of the engine or its basic architecture, modifications affecting existing waste heat recovery hardware on the base engine, implementation of non-CDA variable valve actuation strategies including late intake valve closing, early exhaust valve opening, variable overexpansion Miller timings, EGR pumps, variable compression ratios, turbocharger re-matching, electrically or mechanically driven turbochargers, and electrification of engine accessories or other mild hybridization.

The technology selection effort used a broad funnel approach to make paper assessments of more than 500 different possible combinations of aftertreatment configurations in a down-select process that led to the screening of 33 final technology combinations. The down-selected 33 technology packages were screened using a computer-controlled full-size transient gas reactor (FOCAS® Hot Gas Transient Reactor® (HGTR®)). The HGTR is a computer-controlled burner-based flow reactor system designed to replicate the lean exhaust conditions of the engine and is capable of testing full sized catalyst systems. Five aftertreatment configurations were selected from the HGTR-lab screening for on-engine evaluation before a single configuration was down-selected for a final engine-based full useful life demonstration. Learnings from the work leading to this first system (Stages 1, 1b, and 2) were leveraged during the design and testing of a second engine platform and aftertreatment development (Stages 3 and 3b).

At each major decision point or upon completion of significant milestones the project was reviewed and informed by a meeting of the Program Advisory Group (PAG) consisting of engine OEMs, suppliers, and regulators. Between meetings, the project contractor was available to answer inquires and receive follow-up advice from the PAG members. Major project decisions were then made with the best available information and the PAG input responses that had been offered. The PAG was consulted for input during technology down-selection, for the determination of the accelerated on-engine full useful life aging protocol for this program, and as emissions testing results became available.

The project worked on improving NOx emissions in three areas of operation:

1. Prompt light-off of the emissions controls and minimization of engine-out emissions during the low conversion efficiency operation of the aftertreatment
2. Improved aftertreatment efficiency during loaded transients and steady state with an emphasis on eliminating breakthrough events
3. Maintaining emissions control during low load and idle operation

As mentioned above, this work was performed by SwRI under three separate contracts (Stages 1, 2, and 3), and additional supplemental work assignments called Stage 1b and Stage 3b. CARB staff used these reports for estimating the capabilities of meeting the proposed 2024-2026 requirements with current or modest changes to engine architecture based on input from engine manufacturers on their product planning and research and development lead time requirements. For 2027 and subsequent model year engines, CARB staff evaluated the full suite of technologies on the engine and aftertreatment demonstrated in both Stages 1, 1b, 3, and 3b. Included was the development of a new test cycle under the Stage 2 contract that would demonstrate emission control under urban operation. SwRI also evaluated the most appropriate emission analysis methods for evaluating all engine operations, such as at idle, low loads and high loads that could be evaluated using portable emissions measurement systems for compliance assessment.

Since the beginning of the SwRI Stage 1 contract work in late 2013, there has been much interest by academia and manufacturers of emission control devices to evaluate technologies that enable low NOx emissions without or with minimal impacts to GHG emissions. Many papers have been published on technologies and emission reduction capabilities with current improved and new engine and aftertreatment hardware. Also, papers have been published on in-use testing analysis of in-use vehicles with analysis of different test methods. Some of this work was relied upon by CARB staff to establish appropriate stringency and test methods of CARB staff's proposal as well.

1. 2024 through 2026 Model Year FTP and RMC-SET Assessment

As mentioned above, the technical feasibility of the proposed 2024 through 2026 FTP and RMC-SET NOx standards is supported by data from the SwRI Stage 1 Low NOx Program (Sharp et al., 2017). In this program, SwRI tested a 2014 Volvo MD13TC diesel engine certified to Euro VI standards, but capable of meeting 2010 emissions standards as well. This engine was selected because it also meets the final stringency level 2017 Phase 1 GHG emissions standard three model years earlier than required.

Staff evaluated what near-term strategies and technologies could be used to meet heavy-duty engine NOx emission standards at the proposed 0.050 g/bhp-hr level for the FTP and RMC-SET. First, it is important to understand how the test cycles are constructed and their associated challenges presented to engine designers.

As described in Chapter 1 of this Staff Report, the FTP standard is based on a weighted composite of a cold FTP test (engine typically soaked overnight at set ambient temperature range prior to the test) and a hot FTP test (20-minute engine-off soak period between the FTP tests). The FTP standard is a composite of 1/7th cold FTP plus 6/7th hot FTP. When examining the emission results of the cold and hot FTP tests, it becomes clear that meeting the FTP standards with today's heavy-duty diesel engines, the cold portion of the test is the most significant challenge, and of the most significance when considering lowering the emission standards. As discussed in section 3.2 of the SwRI Low NOx Stage 1 Program report (Sharp et al., 2017), cold FTP emissions (0.71 g/bhp-hr) are 15 times greater than the hot FTP emissions (0.047 g/bhp-hr) for the Volvo MD13TC diesel test engine. Although the hot FTP emission levels could be improved, the cold FTP is the one that needs to be focused on to allow compliance with more stringent FTP standards. A combination of engine calibration, hardware, and exhaust aftertreatment strategies and technologies are available to significantly reduce cold FTP NOx emissions below current standards.

There are engine calibration strategies to improve FTP emissions test performance of heavy-duty diesel engines, especially for controlling the first 600 seconds of the cold FTP cycle (cold start). Cold start strategies utilize a combination of reducing engine-out

NOx emissions while operating the engine in exhaust heat generating mode. Quickly heating up the engine allows for earlier utilization of EGR to control engine-out NOx emissions prior to when the exhaust and SCR aftertreatment system reach elevated temperatures needed to begin controlling emissions. The effectiveness of this strategy is dependent on what type of engine hardware technologies are on the engine. Diesel engines equipped with variable valve train, variable geometry turbocharger, intake or exhaust throttles, or other air handling technologies, have improved capabilities to accelerate thermal energy into the engine and exhaust system while reducing engine-out NOx emissions earlier and more effectively. Section 3.2.4.1 of the SwRI Low NOx Stage 1 Program Report identifies some of these engine technologies on the MD13TC engine that was calibrated to improve thermal management of the engine, namely increasing the idle speed, modified intake throttling, using multiple in-cylinder fuel injections and earlier usage of EGR (Sharp et al., 2017). Figure 8 and 9 below show the engine-out NOx and thermal energy improvements that can be made by improving cold-start calibration alone.

Figure 8. Engine-out Temperature Comparison – Modified Calibration Versus Baseline

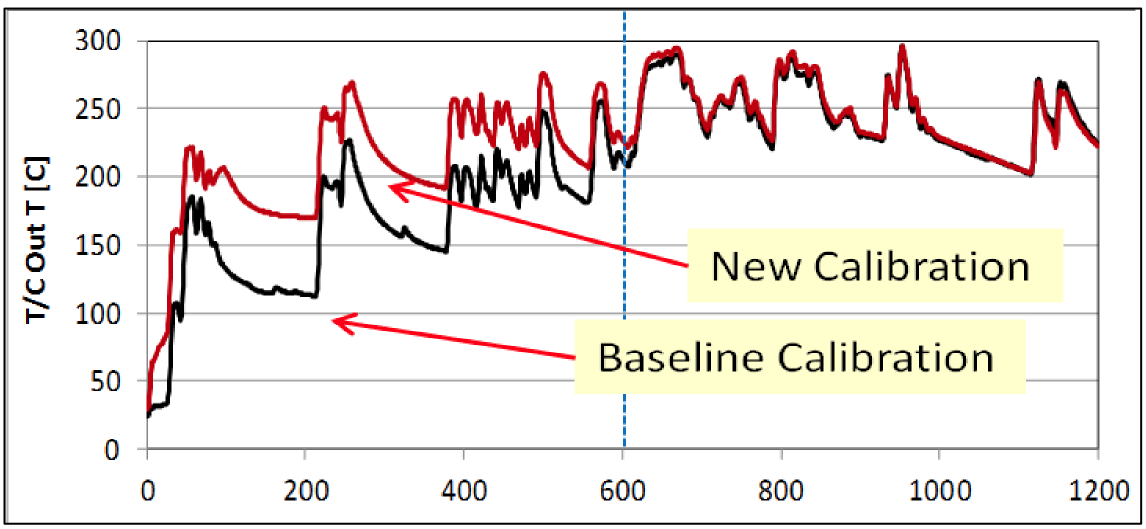
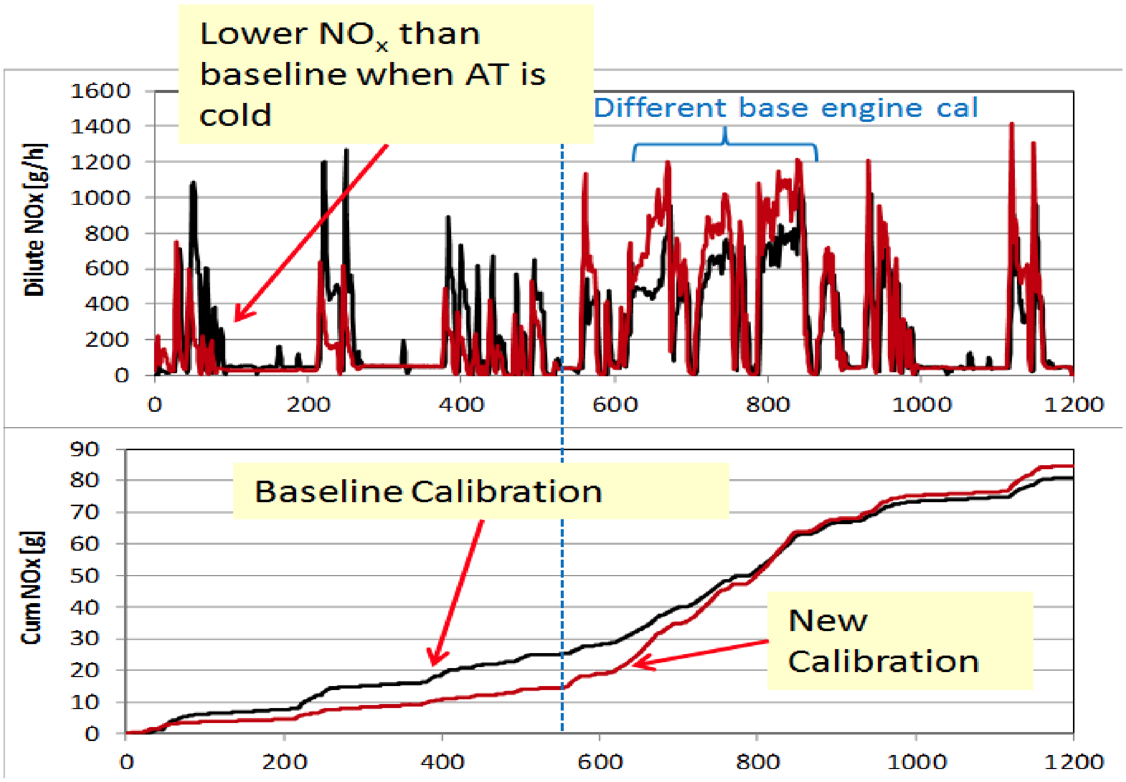


Figure 9. Engine-out NOx Comparison – Modified Calibration Versus Baseline



This new calibration increased fuel consumption on the composite FTP by 0.4 percent (2.5 percent on the cold-FTP) but demonstrated that significant reductions in engine-out NOx and improved thermal performance early in the test cycle can be achieved by improved calibration alone. More thermal energy to the aftertreatment system early in the test cycle enables the NOx aftertreatment system to come online earlier for more effective NOx reduction. Applying this new calibration to the MD13TC engine with its production aftertreatment system reduced composite FTP tailpipe NOx from 0.14 to 0.09 g/hp-hr, a 36 percent reduction solely based on calibration changes to the cold FTP cycle.

Further FTP NOx emission reductions could have been achieved with the MD13TC engine if it had been equipped with other engine hardware technologies, such as EGR-cooler bypass valve and turbocompound bypass valve, which could have further improved thermal management and reduced fuel consumption impacts. The MD13TC engine's hardware architecture was difficult to work with for FTP NOx control because it employs high temperature waste heat recovery in the form of a mechanical turbocompound system for improved fuel efficiency. This system increased the thermal energy sink so that efforts to elevate exhaust temperature in the downstream SCR catalyst were significantly delayed, resulting in higher cold start FTP emissions. Had this engine been equipped with a turbo bypass valve, thermal management during cold start operation would have significantly improved the FTP NOx emissions results. Adding an EGR-cooler bypass valve would have improved NOx emissions results by allowing the use of hot EGR sooner and thereby would have reduced engine-out NOx further during the cold start portion of the test cycle. CARB staff believes that engine manufacturers would likely utilize EGR-cooler bypass valve in their future engine designs to meet the proposed 2024 standards and hence included this technology in the cost assessment described in Chapter IX of this Staff Report.

Further improvements to the exhaust aftertreatment systems could also be made. SCR aftertreatment systems require adequate exhaust temperatures (today typically above 180˚C) to work. Such systems use a reductant (liquid urea) introduced into the exhaust stream to perform the catalytic reaction that reduces NOx emissions, typically at temperatures above 180˚C. As shown on Figure 9 above, depending on engine calibration, the SCR system on the MD13TC engine was not activated until after 50 seconds (new calibration) or after 200 seconds (baseline calibration). Until the time the SCR system is activated, NOx emissions remain high. The time delay between when the engine is turned on and when the SCR is warm enough to be activated is a function of the amount of energy coming out of the engine and the thermal mass inertia that absorbs that energy between the engine and SCR system. A straightforward approach that manufacturers could use to shorten this time delay and thereby cut NOx emissions would be to reduce the thermal mass between the engine and SCR. Manufacturers could do this by modifying the SCR placement in the exhaust system (moving it closer to the engine) or by placing the entire aftertreatment system closer to the engine. Insulating the engine exhaust manifold and exhaust pipe could also help, but to a lesser degree.

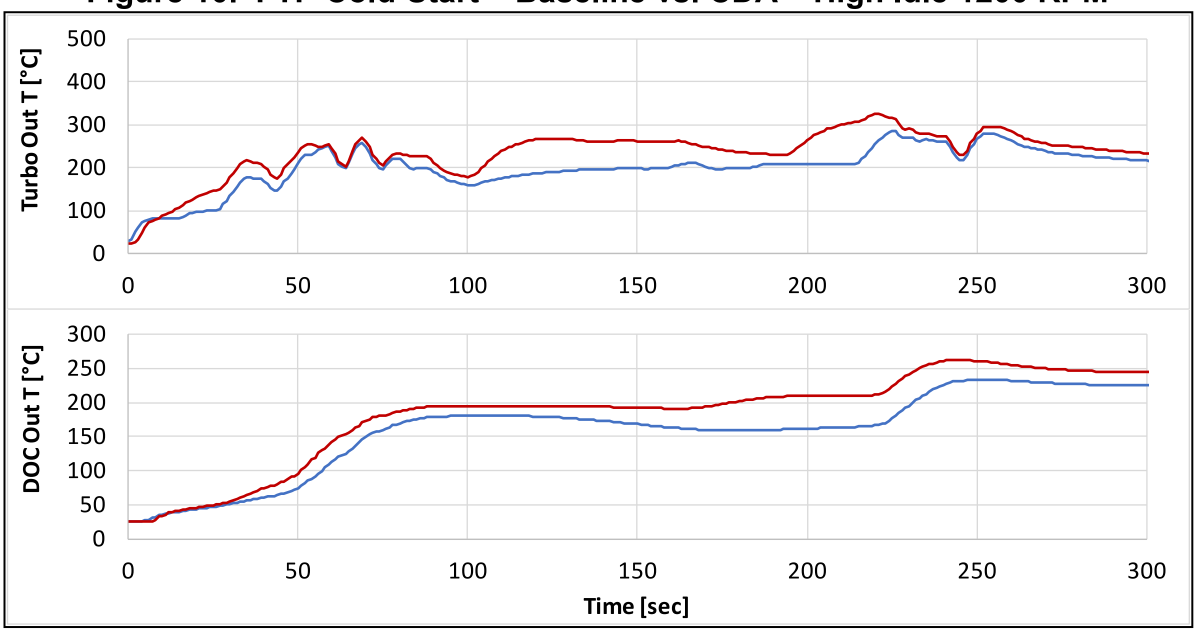
An additional approach would be to enable the use of SCR sooner for better NOx control during FTP cold start. SCR systems could be used earlier if enough heat were provided to the reductant (liquid urea). Irreparable damage can occur to the SCR system if urea is introduced at temperatures below 180˚C and liquid urea makes its way onto the catalyst. For proper function, urea liquid needs to be disassociated into ammonia (NH3), CO2 and water before it reaches the catalyst. This disassociation is a function of temperature and how small the mist droplets of urea liquid are when introduced into the exhaust stream. Another approach is to spray the urea over a hot surface or preheat the urea and inject it under pressure. These heated dosing approaches would make SCR control available much sooner in the test cycle and significantly reduce cold start emissions. CARB staff believes that engine manufacturers would likely utilize heated urea dosing in their future engine designs to meet the proposed 2024 standards.

CARB staff also expects that manufacturers would use larger SCR catalyst bed volumes and improved catalyst substrates to achieve further improvement on the hot FTP test cycle. This improvement would likely be the predominant method manufacturers would use for meeting the RMC-SET test cycle performance, especially on the high engine-load test points of the cycle.

2. *Engine Hardware Technology assessment*

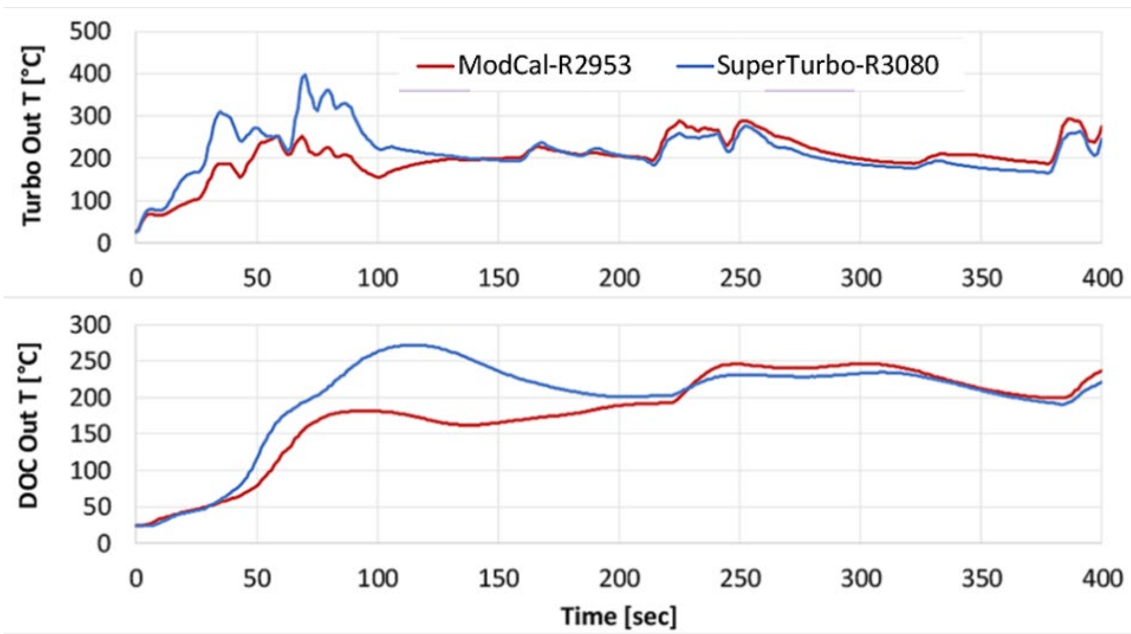
As mentioned above, the well-controlled FTP emissions during the later portion cold start and the hot start cycles leave an emissions challenge dominated by emissions that occur during cold start. To control FTP emission levels to at or below 0.020 g/bhp-hr requires significantly reduced engine-out NOx emissions during engine start and providing sufficient heat energy to obtain SCR catalytic control within the first minute after engine start. In SwRI Stage 3 and 3b, a 2017 Cummins X15 diesel-fuel heavy-duty engine was paired with an Eaton CDA valve system that was purposely designed to operate on this engine (Morris & McCarthy, 2020; Neely et al., 2020a). Under low load condition, the CDA system becomes active and shuts down some of the engine cylinders, thereby shifting the engine load on the few cylinders in operation. This strategy has the benefits of increasing exhaust heat coming out of the engine, reducing overall exhaust flow out of the engine and reducing fuel consumption. SwRI integrated and calibrated the paired system with the help of Cummins and Eaton and implemented CDA firing order strategies to mitigate the potential for changes in operation to unintentionally risk unacceptable noise, vibration, and harshness, and potentially damaging engine vibration (Neely et al., 2020b). Figure 10 below shows the higher exhaust temperatures achieved with CDA (red) active versus the baseline engine (blue) at the same fuel rate (or less fuel rate at the same test point due to CDA improvements in engine efficiency).

Figure 10. FTP Cold-Start – Baseline vs. CDA – High Idle 1200 RPM



There are other engine technologies and strategies that reduce the time for active SCR control through improved thermal performance. For example, the Cummins engine used for SwRI Stage 3 testing spent some time doing initial benchmarking of a new type of air handling system that has the flexibility to act as either a turbocharger or supercharger, called the SuperTurbo (as briefly described earlier). This system was benchmarked as received but was not used in the Stage 3 demonstration because full optimization of the engine and turbo compressor and turbine was beyond the scope of this project. This technology also demonstrated the ability to significantly reduce the time to elevate exhaust temperature during cold start, however, with a modest 1.1 percent fuel penalty during the cold start portion of the test. The thermal performance of the SuperTurbo is shown in Figure 11 below with the red line showing thermal performance with only modified cold calibration strategy[1] (without SuperTurbo) and the blue line showing thermal performance with both modified cold calibration and SuperTurbo (Neely et al., 2020a).

Figure 11. FTP Cold-Start – SuperTurbo Thermal Performance

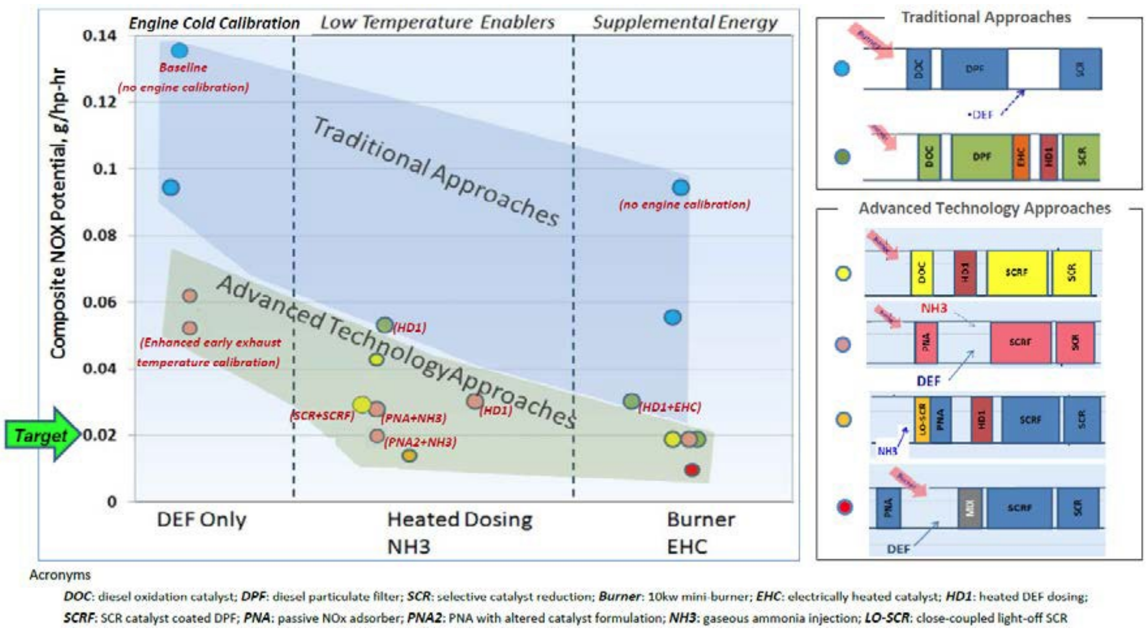


3. *Aftertreatment Technology assessment*

There were many aftertreatment technologies and strategies evaluated at SwRI in Stage 1 and Stage 3. Figure 12 below shows the technologies considered.

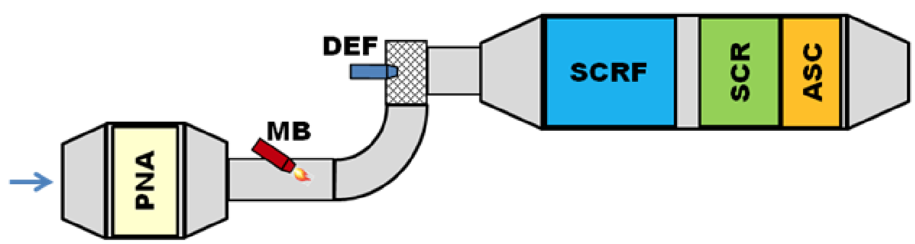
[1] SwRI's modified cold calibration strategy included increased EGR rates, multiple fuel injections, and increased idle speed during the early idle periods of the FTP. The objective of this strategy is to increase exhaust temperatures during cold starts and reduce engine-out NOx.

Figure 12. Composite Low NOx Potential of Various Technology Configurations



For Stage 1 testing of the MD13TC engine, it was decided that the best approach for this engine would be to control cold-start emissions with a PNA with a built-in DOC for NO2 generation for the PM filter, a fuel burner or mini burner (MB), to generate exhaust heat, SCR catalyst coated on the DPF (SCRF), another traditional downstream SCR system for further NOx control, and an ASC to control any ammonia slipping past the SCR. Figure 13 below shows how this aftertreatment system was configured.

Figure 13. Stage 1 Aftertreatment Configuration



The MD13TC engine had significant thermal mass that made it very difficult to control cold-start emissions and to generate enough exhaust heat downstream of the exhaust system to achieve accelerated SCR control needed to reach 0.02 g/bhp-hr FTP NOx emission levels. The PNA is designed to capture and store lower temperature engine-out NOx emissions while the mini burner elevates exhaust temperature to activate the SCR control prior to the PNA reaching capacity and exhaust temperatures above 200˚C when the PNA starts to lose its ability to hold on to NOx and starts releasing NOx into the exhaust stream. The SCRF is used to further reduce exhaust thermal mass so that catalytic control of NOx can begin sooner, so that fuel efficiency and reduced GHG emissions impacts could be minimized.

In Stage 1, SwRI used development-aged aftertreatment parts received by emission component suppliers to perform needed calibration on the engine-aftertreatment system to demonstrate the NOx reduction capabilities of the engine-aftertreatment system. Development-aged parts are emission control parts that have been hydrothermally aged on a bench to a designed useful life, in this case it was aged to the equivalent of 435,000 miles to account for thermal degradation of the system over the engine's design life.

In order to get better representative real-world aging on the aftertreatment system, SwRI had developed an accelerated aging procedure that provides both thermal and chemical aging. The initial aging in Stage 1 experienced a mechanical failure of the can holding the PNA in place that dislodged insulating material on-to and inside the SCRF substrate. Despite the significant process upset condition endured as a result of the debris flow plugging during aging, this original set of hardware still returned 0.035 g/bhp-hr FTP NOx performance at the end of full useful life aging. A second effort was made to obtain new aftertreatment parts and perform the same aging procedure under a supplemental contract called Stage 1b. Stage 1b aging was completed without issues and the test results of the baseline engine, and the engine with new engine calibration and advanced aftertreatment system thermally aged and thermal and chemical aged, are presented in Table 1 below.

Table 1. Diesel Engine NOx Emissions Comparison – Low NOx Engine Versus Baseline, (g/hp-hr)

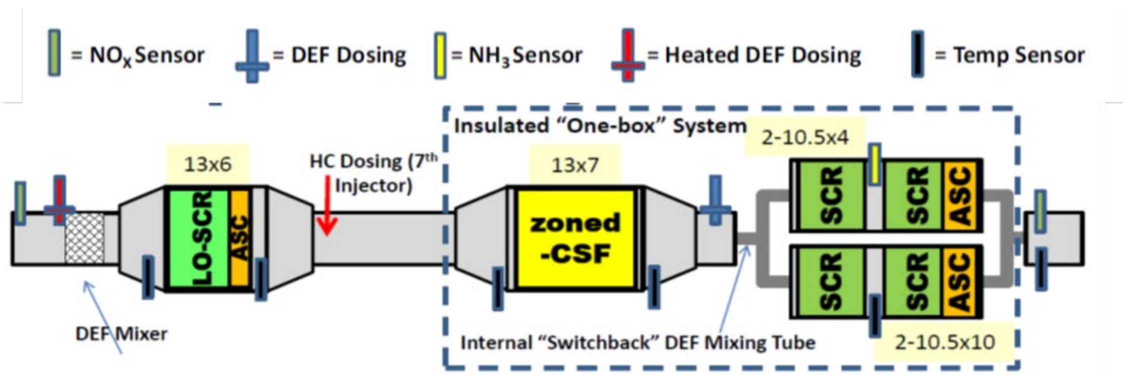
<table>
<tr><th colspan="2" rowspan="2">Engine</th><th colspan="3">FTP</th><th rowspan="2">RMC_SET</th></tr>
<tr><th>Cold</th><th>Hot</th><th>Composite</th></tr>
<tr><td colspan="2">Baseline</td><td>0.710</td><td>0.047</td><td>0.140</td><td>0.084</td></tr>
<tr><td rowspan="3">Low NOx Engine</td><td>Stage 1
DevAged</td><td>0.062[a]</td><td>0.008</td><td>0.016</td><td>0.015</td></tr>
<tr><td>Stage 1b
Final Parts - Fresh</td><td>0.025</td><td>0.005</td><td>0.009</td><td>0.001</td></tr>
<tr><td>Stage 1b
Final Parts - Aged</td><td>0.109</td><td>0.009</td><td>0.023</td><td>0.032</td></tr>
<tr><td rowspan="2">% Reduction from Baseline</td><td>Stage 1
DevAged</td><td>91%</td><td>83%</td><td>89%</td><td>82%</td></tr>
<tr><td>Stage 1b
Final Aged</td><td>85%</td><td>81%</td><td>84%</td><td>62%</td></tr>
</table>

[a] Note: Development PNA was slightly compromised by raw fuel exposure due to a cold-start engine malfunction that occurred during development.

Although this Stage 1 demonstration's development aged parts met the 0.020 g/bhp-hr NOx emissions target set at the start of the program, further, more rigorous on-engine aging demonstrated similarly significant NOx emission reduction compared to the baseline engine and aftertreatment system. The emissions performance despite the unrepresentative extra aging encountered by the first set of parts also speaks to the robustness of the catalyst approach.

As mentioned previously, the MD13TC engine in Stage 1 was difficult to work with because this engine and waste heat recovery hardware presented a worst case when considering thermal mass and modifying engine hardware, and the turbocompound system were beyond the scope of the project. Thus, it was determined to obtain funding for a second effort that would select a diesel engine with capabilities to alter or change engine hardware and would be more representative of the engine architectures used in the United States. As mentioned above, Stage 3 used a Cummins X15 diesel engine that had prototype engine hardware available. It was also decided that the aftertreatment technologies selected should be similar to the technologies used on today's heavy-duty diesel engines so the aftertreatment selected for this engine was comprised of a close-coupled SCR (light-off SCR or LO-SCR) with zone coated ASC, a CSF, and a dual parallel path SCR followed in each branch by a zone coated ASC. This advanced aftertreatment package was also equipped with a heated DEF dosing system coupled with the LO-SCR. Figure 14 shows the aftertreatment configuration.

Figure 14. SwRI Stage 3 Final Aftertreatment System



The advantage of this system is the reduction of mass between the engine and LO-SCR catalyst for significantly reducing the time for starting SCR control. The heated LO-SCR dosing system enabled further reduction in the time between engine start and SCR control. With the addition of engine cold calibration and CDA, as described above, the tailpipe exhaust performance for the baseline, development-aged aftertreatment parts, and with final aftertreatment system fresh and thermally and chemically aged to 1/3 of the useful life showed significant NOx and some GHG emission reductions, as shown in Figures 15 and 16 (Sharp, 2020).

Figure 15. Stage 3 Engine-Aftertreatment NOx Emissions Performance

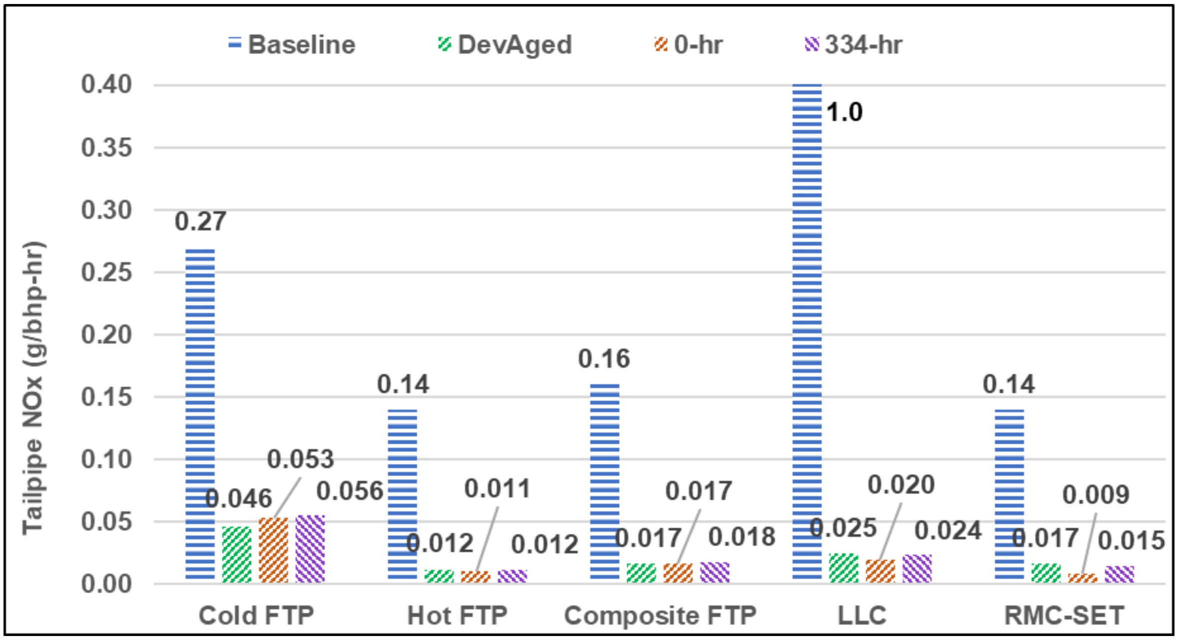
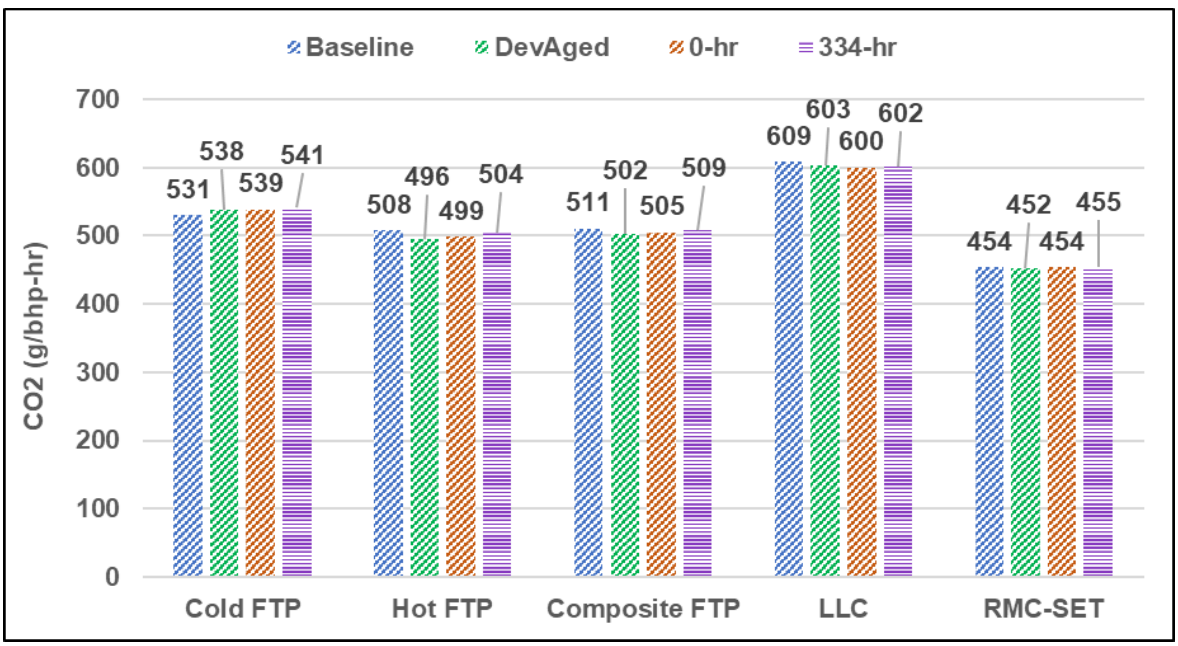


Figure 16. Stage 3 Engine-Aftertreatment GHG Emissions Performance



Date of Release: June 23, 2020
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