NEXT TIER OFF-ROAD DIESEL AFTERTREATMENT TECHNOLOGY FABRICATION AND OPTIMIZATION

OFF-ROAD LOW NO_X DEMONSTRATION PROGRAM – STAGE 2

ARB CONTRACT 19RD025

FINAL REPORT

SwRI® Project Number 03.26041

Prepared for:

California Air Resources Board
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December 16, 2022

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POWERTRAIN ENGINEERING DIVISION

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LIST OF ACRONYMS

°C	Degrees Celsius
ANR	Ammonia to NO_X Ratio
ASC	Ammonia Slip Catalyst
AT	Aftertreatment
ATM	Aftertreatment Trap Management Mode
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
CAN	Controller Area Network
CARB	California Air Resources Board
CCV	Closed Crankcase Ventilation
CDA	Cylinder Deactivation
CF	Cylinder Fire
CFR	Code of Federal Regulations
CH_4	Methane
CITT	Curb Idle Transmission Torque
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COV	Coefficient of Variation
CSF	Catalyzed Soot Filter
CWF	Carbon Weight Fraction
DAAAC	Diesel Aftertreatment Accelerated Aging Cycles
DEF	Diesel Exhaust Fluid (32% urea by weight)
DSF	Dynamic Skip Fire
dDSF	Diesel Dynamic Skip Fire
$deSO_X$	Desulfation
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
ECM	Electronic Control Module
ECT	Engine Coolant Temperature
EGR	Exhaust Gas Recirculation
EO	Engine Out
EU	European Union
FE	Fuel Economy
FF	Firing Fraction
FSN	Filter Smoke Number
FTIR	Fourier Transform Infrared
FTP	U.S. Heavy Duty Transient Federal Test Procedure
FUL	Full Useful Life
g/bhp-hr	Grams Per Brake Horsepower-Hour
g/kW-hr	Grams Per Kilowatt-Hour
GHG	Greenhouse Gas
H_2O	Water
HC	Hydrocarbons
HDIUT	Heavy Duty In-Use Testing
hp	Horsepower

HW	Hardware
IMAP	Intake Manifold Absolute Pressure
IMT	Intake Manifold Temperature
IRAF	Infrequent Regeneration Adjustment Factor
kg/hr	Kilograms Per Hour
kW	Kilowatt
LFE	Laminar Flow Element
LLC	Low Load Cycle
LLAC	Low Load Application Cycle
LO-SCR	Light-Off SCR Catalyst
LTT	Long term trim
MAW	Moving Average Window
MB	Mini-burner
MECA	Manufacturers of Emission Controls Association
MFC	Multi-Function Catalyst (LO-SCR with local oxidation capacity)
MY	Model Year
N_2O	Nitrous Oxide
NAAQS	National Ambient Air Quality Standard
NH_3	Ammonia
NIST	National Institute of Standards and Technology
Nm	Newton-Meter
NMHC	Nonmethane Hydrocarbons
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NO_X	Oxides of Nitrogen
NRTC	Nonroad Transient Cycle
NTE	Not-to-Exceed
NVH	Noise, Vibration, and Harshness
OBD	Onboard Diagnostics
OCV	Open Crankcase Ventilation
PAG	Program Advisory Group
PGM	Platinum Group Metals
PM	Particulate Matter
PNA	Passive NO_X Adsorber
ppb	Parts Per Billion
ppm	Parts Per Million
rad/s^2	Radian Per Second Squared
RMC	Ramped Modal Cycle (C1 8-Mode for Variable Speed Engines)
RMC-SET	Ramped Modal Cycle Supplemental Emission Test
RMS	Root Mean Square
rpm	Revolutions Per Minute
SCR	Selective Catalytic Reduction (ammonia-based)
SCR_WU	SCR Warm-Up Mode
SCRF	SCR on Filter (SCR coated on DPF)
SO_2	Sulfur Dioxide
SwRI	Southwest Research Institute
SPN	CAN Suspect Parameter Number
THC	Total Hydrocarbons

TM	Thermal Management
TM-1	Aggressive Thermal Management
TM-2	Low Thermal Management
TP	Tailpipe
U.S.	United States
UAF	Upward Adjustment Factor (for Infrequent Regeneration)
VGT	Variable Geometry Turbine
zCSF	Zone-Coated Catalyzed Soot Filter

ABSTRACT

This program is part of a continuing effort aimed at demonstration of the capability of diesel emission control technologies to reach low oxides of nitrogen (NO_X) levels on an off-road diesel engine. The program objective is to demonstrate the feasibility of technologies to reach tailpipe NO_X emission reductions of up to 90% from the current Tier 4 Final standards, and particulate matter (PM) emission reductions of at least 75% from the current Tier 4 Final standards. Two different systems are being developed to meet these targets, the first of which is intended to meet the target NO_X and PM levels with no impact on greenhouse gas (GHG) emissions. The second system is intended to meet the target NO_X and PM levels while also demonstrating a 5% to 8.6% improvement in carbon dioxide (CO_2) emissions, and remaining GHG neutral with respect to N_2O and CH_4. The demonstration is targeted primarily at off-road engines rated between 56 kilowatts (kW) and 560 kW. The off-road Low NO_X demonstration reported here builds on previous extensive efforts to demonstrate Low NO_X technologies for on-road engines [1][2][3][4][5], as well as the previous off-road test program that was intended to lay the groundwork for the current effort. Efforts will also continue towards a final robust performance demonstration of an optimized system configuration and full useful life (FUL) durability out to both the current 8,000-hour requirement, and to an extended 12,000-hour level. The emission control systems demonstrated in this program showed good promise in being able to reach levels 25% to 50% below the 90% NO_X emission reduction target levels with technologies suitable for implementation in production, allowing for a significant potential compliance margin. However, work is continuing under the follow-on contracts to complete the necessary steps for a fully robust demonstration.

EXECUTIVE SUMMARY

Despite decades of progress in cleaning the air, California continues to struggle with some of the most difficult air quality issues in the United States (U.S.); the South Coast and San Joaquin Valley air basins are classified as Extreme nonattainment areas for the 70 parts per billion (ppb) federal ozone standard and have a significant number of disadvantaged communities. Nineteen areas of California are designated as nonattainment. The California Air Resources Board (CARB) has stated that meeting federally mandated ozone limits of the National Ambient Air Quality Standard (NAAQS) will require significant reductions in ozone forming oxides of nitrogen (NO_X) emissions across a wide range of applications. NOx emissions contribute heavily to ambient fine particulate matter (PM) pollution as well. Off-road diesel engines remain one of the most significant contributors to the overall NO_X inventory, and CARB has indicated that reductions as large as 90% from current standards may be necessary to achieve air quality goals.

Previously, CARB initiated a series of programs at the Southwest Research Institute (SwRI) to demonstrate the technical feasibility of reaching low NO_X levels up to 90% below the current standards for on-road engines. The goal of this program was to leverage that previous research and extend the low NO_X technology demonstration to the off-road market. The program goal for low NO_X was 0.04 grams per kilowatt-hour (g/kW-hr) over the current regulatory test cycles, with low load and in-use emissions as low as feasible. In addition, the program would also demonstrate PM levels below 0.005 g/kW-hr, more than 75% below the current Tier 4 Final standard. As an added element to the program, and in coordination with the later CARB contract 20MSC005, one technology package (i.e., Package 2) was also tasked to demonstrate reductions in CO_2 on the order to 5 to 8.6% (equivalent to Phase 1 on-road CO_2 reductions), while meeting the low NO_X and PM targets at the same time. In both cases, the program's intent was to reach these targets with technologies that are feasible for production in the off-road market by the 2028 or 2029 model year (MY)..

Figure 1 shows a summary of the tailpipe NO_X emission levels demonstrated in this program. It should be noted that these levels were demonstrated with aftertreatment hardware that was hydrothermally aged to full useful life (FUL) equivalent, though this is not as rigorous as the final aging methods that will be used in the continuing program efforts that will consider both thermal and chemical aging mechanisms.

As can be seen in Figure 1, tailpipe emissions were reduced by 90% compared to the Tier 4 engine on the Nonroad Transient Cycle (NRTC), by 75% on the high load Ramped Modal Cycle (RMC), and by over 99% under the light load conditions of the Low Load Application Cycle (LLAC) that are below the loads of the current certification requirements for both Packages 1 and 2. The results were demonstrated using a conventional aftertreatment architecture utilizing a single module system incorporating diesel oxidation catalyst, diesel particulate filter, and selective catalytic reduction (DOC+DPF+SCR) technologies, as depicted below in Figure 2, and incorporating closed crankcase ventilation (CCV) which is already in use on some on-road engines. These results enabled projections of end-of-life performance after accounting for real system durability and the impacts of regeneration. The projections indicated margins of 25% to 50% in most cases, although further work on the Package 2 RMC cycle is needed to realize this same level of margin.

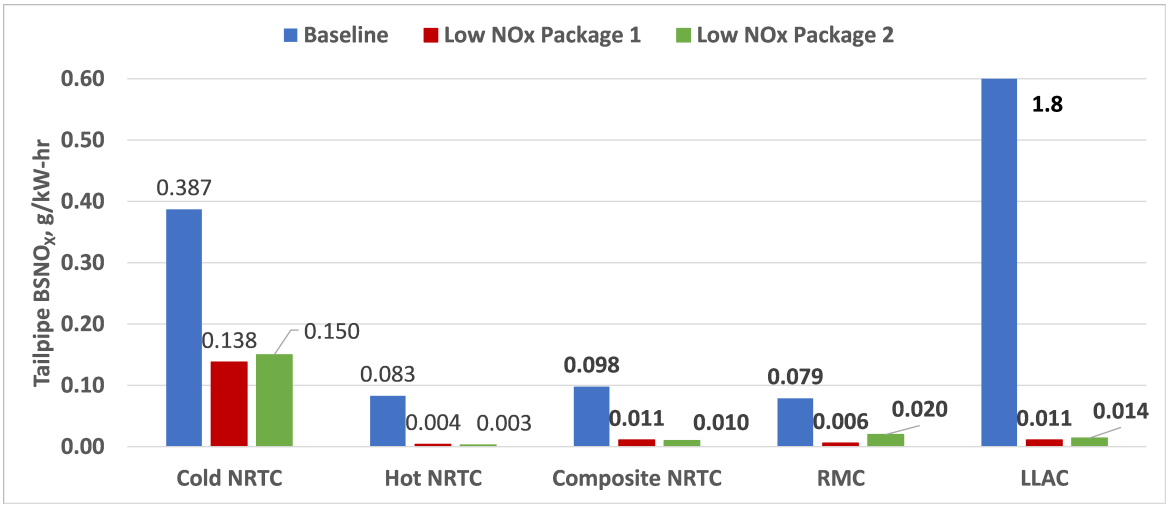


FIGURE 1. TAILPIPE BSNO$_X$ EMISSIONS FOR LOW NO$_X$ SYSTEMS COMPARED TO BASELINE TIER 4 ENGINE

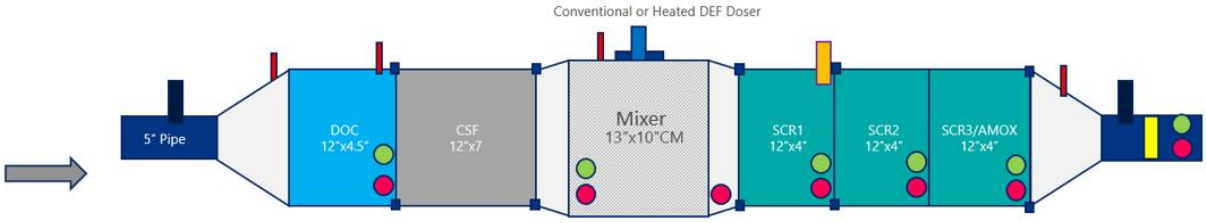


FIGURE 2. DEMONSTRATION AFTERTREATMENT SYSTEM ARCHITECTURE (DOC+DPF+SCR)

Figure 3 gives a summary of carbon dioxide (CO_2) emissions for the low NO$_X$ systems as compared to the Tier 4 baseline engine. For Package 1, the target emission levels shown above were reached with no penalty to GHG emissions. For Package 2, which included further modified engine calibrations and cylinder deactivation (CDA) technology utilizing dynamic skip fire (DSF) controls, the low NO$_X$ emission levels were achieved along with CO_2 reductions of about 4 to 8 percent.

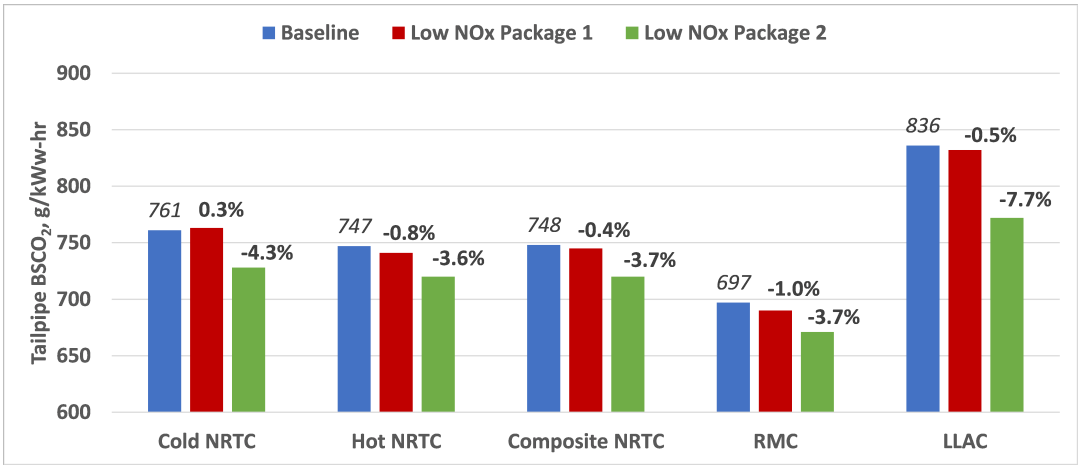


FIGURE 3. CO_2 EMISSIONS FOR LOW NO$_X$ SYSTEMS COMPARED TO BASELINE TIER 4 ENGINE

Efforts are continuing under the parallel contract 20MSC005, which will continue to examine opportunities for CO_2 reduction, as well as demonstrating system performance over rigorous aging methods simulating thermal and chemical aging (such as oil and sulfur poisoning) out to 12,000 hours of extended useful life.

1.0 INTRODUCTION AND BACKROUND

This report details the results of a program that represents a further continuation of efforts to demonstrate low oxides of nitrogen (NO_X) technologies at Southwest Research Institute (SwRI) on behalf of the California Air Resources Board (CARB) since 2014. In particular, this report describes the extension of those previously documented efforts into the off-road diesel engine market. The effort detailed herein comprises what is generally referred to as Stage 2 of the Off-road Low NO_X Demonstration Program and was conducted under CARB Contract 19RD025. This Stage 2 program builds on previous efforts conducted under the Stage 1 off-road program (CARB Agreement No. 18RD006). Further it should be noted that this effort was in part conducted in parallel with efforts contracted under CARB Contract 20MSC005. That parallel effort further expanded the scope of the program to examine the potential for greenhouse gas (GHG) reductions, as well as a continuing effort to complete the technology demonstration efforts with robust aging systems to extended useful life of up to 12,000 hours.

This program also leveraged experience and understanding that was gained during previous technology demonstration efforts conducted in support of the development of the CARB on-road Low NO_X Omnibus rule[1][2][3][4][5], which was adopted by the Board in August, 2020. It is understood that the efforts documented in this report, as well as the continuing work under 20MSC005 will be used to support the development of a Tier 5 Off-road rulemaking. That development effort was publicly announced by CARB during a workshop on November 3, 2021.

The target for this program was to demonstrate emission technologies which would enable an off-road diesel engine having rated power above 56kw to achieve tailpipe NO_X emission levels 90% below the current Tier 4 Final standards, and PM emission levels 75% below the current Tier 4 Final standards. This would translate to a tailpipe NO_X target of 0.04 g/kW-hr and a tailpipe particulate matter (PM) target of 0.005 g/kW-hr. These targets need to be demonstrated at the end of the regulatory useful life for these engines, which is currently set at 8,000 hours of operation for Tier 4 engines. With the addition of the scope under 20MSC005, the target useful life for the demonstration was revised upwards to 12,000 hours of operation.

The initial program scope was to examine a number of different technology options and from those options down-select two different technology “packages” that could demonstrate the potential for meeting the tailpipe NO_X and PM targets described above. These technologies would be integrated onto a base Tier 4 off-road engine having a nominal power rating of 225hp to 275hp (168kw to 205kw). For this initial demonstration phase, the aftertreatment (AT) systems would be hydrothermally aged to full useful life (FUL) using an accelerated process that will be described later in the report. Although GHG emission targets were not explicitly defined within the original RFP for 19RD025, it was understood that there was a desire to meet the tailpipe emission targets with a system that did not result in any significant increase in GHG emissions over levels documented for the baseline Tier 4 engine.

The program focused on off-road certification duty cycles, which for the target engine are the Nonroad Transient Cycle (NRTC) and the 8-Mode C1 Ramped Modal Cycle (RMC) for variable speed engines. In addition, the low load operating space was covered through the use of the off-road Low Load Application Cycle (LLAC) that was developed in the previous program under contract 18RD006. The LLAC did not have a specific emission target, but instead the intent

was to reach as low a tailpipe NO_X level as feasible while maintaining CO_2 emissions at or below the levels observed for the baseline engine.

It should be noted that the PM targets for the program were met in a relatively straightforward fashion through the incorporation of diesel particulate filter (DPF) technology that is already in production for both off-road and on-road engines. Therefore, the majority of the program effort was expended on examining NO_X control options and balancing those options and the desire to not increase CO_2 emissions. However, maintaining reasonable engine-out soot levels and good passive regeneration capability over most of the operating cycles were still important priorities for the program.

With the addition of scope under the parallel contract 20MSC005, a desire was expressed to also examine the potential for GHG reductions while still meeting the tailpipe emission targets below. This was expressed as a CO_2 reduction target of between 5% and 8.6% reduction from the baseline Tier 4 engine. As a result the targets for the two emission control "packages" under the current effort were altered as follows:

- Package 1, designated as the "Low Cost" package, would be targeted to demonstrate the original program goals of meeting tailpipe emission targets of 0.04 g/kW-hr NO_X and 0.005 g/kW-hr PM, while targeting CO_2 levels equivalent to the baseline Tier 4 Final engine.

- Package 2, designated as the "Low GHG" package would be targeted to demonstrate tailpipe emission targets of 0.04 g/kW-hr NO_X and 0.005 g/kW-hr PM, while at the same time targeting a reduction in CO_2 of 5% to 8.6% from the baseline Tier 4 Final engine.

For both technology packages, the AT systems would be hydrothermally aged to the equivalent of 12,000 hours of useful life, as opposed to the originally planned 8,000 hours. It should be noted that under the following contract, 20MSC005, one of these two systems will later be aged to that same 12,000-hour target using the more rigorous and representative aging methodology of the Diesel Accelerated Aftertreatment Aging Cycles (DAAAC) protocol, which will involve both thermal and chemical aging at a 10X acceleration rate. However, that effort is outside the scope covered under this report.

It should be noted that the effort documented in this report represents an initial examination of technology options, and their potential for reaching the desired emission targets. Work efforts will continue under the following contract to further refine technology choices and optimize the final package results.

2.0 METHODS AND MATERIALS

2.1 Test Engine

The test engine for this program was a 2018 model year (MY) John Deere 6068 diesel engine which met Tier 4 Final emissions standards. The engine installed in the transient emission test cell at SwRI is shown in Figure 4. The engine selected for this program was calibrated at a nominal 187 kw maximum power rating at 2200 rpm. It was supplied to the program by Deere, along with the stock AT system. Both the engine and the AT system had previously been de-greened as part of the prior baseline work under contract 18RD006. A summary of some basic engine parameters for this test engine is given in Table 1 below.

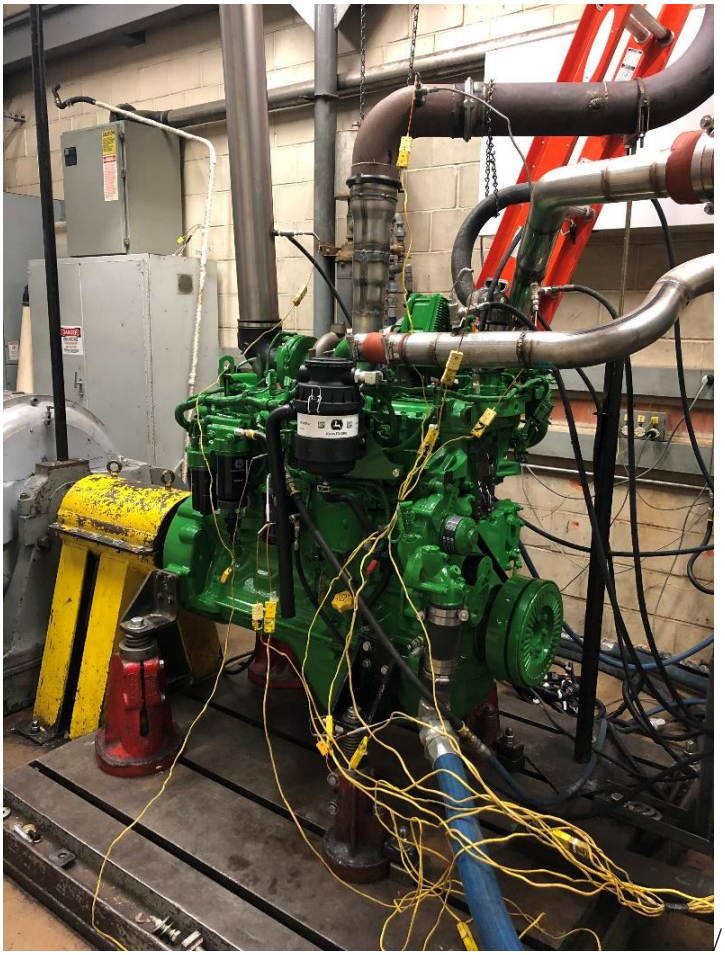


FIGURE 4. TIER 4 JOHN DEERE 6068 ENGINE

TABLE 1. JOHN DEERE 6068 ENGINE PARAMETERS

Parameter	Value
Configuration	Inline 6 cylinder
Bore x Stroke	106 x 127 mm
Displacement	6.8 L
Compression Ratio	16.7 : 1
Rated Power	187 kW (251 hp)
Rated Speed	2200 rpm
Peak Torque	1026 Nm
Peak Torque Speed	1600 rpm
Test Fuel	2-D Cert. Diesel

The engine was an inline 6 cylinder diesel engine that was turbocharged and intercooled, with a dual stage series turbocharger arrangement featuring a variable geometry turbine (VGT) as the high pressure turbocharger. The engine utilized cooled exhaust gas recirculation (EGR) as a primary means of engine-out NO_X control. The engine also featured an intake throttle to help regulate engine air flow and drive EGR under some engine conditions. The fuel injection system was capable of supporting multiple pilot and post injection events, and was capable of both near and far post injections. For the stock engine, DPF regeneration was generally performed using post-injection, rather than in-exhaust injection.

Deere also supplied a significant amount of hardware and engineering support for this program, including calibration access to the engine electronic control module (ECM) using proprietary engineering tools. Deere also supplied a cylinder head machined and prepared to allow the measurement of cylinder pressure in all 6 cylinders. Significant additional electronic and engineering support for controls development was also provided by Deere, as detailed later in the section covering controls.

The stock Deere AT system was a conventional DOC+DPF+SCR architecture, with the canning arrangement being two can “switchback” style assembly. The diesel oxidation catalyst (DOC) and DPF are in the first can followed by a dosing and mixing tube, and finally a second can, containing the selective catalyst reduction (SCR) catalysts. The stock AT system is shown in Figure 5 and Figure 6, depicted from the inlet and outlet sides, respectively. The outlet view also shows the transfer pipe from the engine, which was sized to match a representative (but somewhat long) machine installation, and verified to be within the temperature drop specifications given by Deere. The system used a Bosch Denoxtronic 2.2 Diesel Exhaust Fluid (DEF) injection system, which utilized an engine-water cooled injection nozzle. An ammonia slip catalyst (ASC) was coated on the rear of the SCR catalyst substrate.



FIGURE 5. BASELINE (STOCK) AFTERTREATMENT (INLET SIDE) FOR 2018 DEERE 6068 ENGINE



FIGURE 6. BASELINE (STOCK) AFTERTREATMENT SYSTEM FOR DEERE 6068 ENGINE – OUTLET SIDE AND DOSING-MIXING PIPE

2.2 Emission Test Cell

This program was performed by the Powertrain Division at SwRI in the primary emissions laboratory in Building 87, with the engine installed in Transient Emission Cell 19. This test cell was a transient capable test cell meeting the requirements of 40 CFR Part 1065 and 40 CFR Part 1039 for emission certification testing on off-road engines. It features a full-flow constant volume sampling dilution tunnel, and incorporates both Raw and Dilute Continuous emission measurements.

Primary tailpipe emission measurements were performed via Dilute Continuous sampling using the constant volume sampling dilution tunnel. A Horiba MEXA 7200D dilute emission bench was used for measurements of THC, CH_4, NMHC, CO, CO_2, and NO_X. Tailpipe PM measurements were made via SwRI's proprietary secondary dilution system. In addition to the Dilute measurements, a Fourier Transform Infrared (FTIR) instrument was also used in the raw exhaust at the tailpipe to monitor NO, NO_2, NH_3, N_2O, and SO_2, as well as CO_2 and other gases for quality assurance purposes. The FTIR was attached to a manifold that allowed measurements at multiple points along the AT system to aid in AT development and calibration, as well us to understand various aspects of AT behavior.

Engine-out emissions were also monitored using Raw measurement techniques. A Horiba MEXA 7100DEGR raw emission bench was used for engine-out measurements of THC, CO, CO_2, NO_X, NO, and O_2, as well as intake manifold CO_2 measurement to allow for independent calculation of the EGR rate. Raw exhaust flow measurement was performed via intake air flow measurement using a laminar flow element (LFE) and the chemical balance calculations in 40 CFR Part 1065.650 and 1065.655. During initial baseline tests, engine-out PM was also measured via a Sierra BG3 partial flow dilution system. The partial flow dilution system was used only to establish baseline engine-out PM rates, and again later to verify engine-out PM rates on the Low NO_X engine during development.

To support combustion and hardware development, an SwRI proprietary high-speed data acquisition system was used to monitor cylinder pressure and fuel injector current on all 6 cylinders. This system was also used to monitor valve proximity sensors to verify cylinder deactivation (CDA) when that technology was being examined. This was crucial for the development and monitoring of systems such as CDA, as well as for monitoring combustion stability and performance during calibration development. This system was also used to monitor the timing and triggering of the CDA valve actuators during the initial implementation and development stages for that system.

Most of the additional sensors and actuators used for the program were Controller Area Network (CAN)-based, and multiple CAN buses were monitored and recording along with the test cell data. In addition, proprietary control channels were monitored via both ASAP3 for the engine, and CAN for the SwRI integration controller systems. This allowed all data to be recorded and synched onto the SwRI test cell host computer for later ease of use and analysis.

All testing, emission calculations, and test cell quality assurance procedures were conducted in accordance with procedures given in 40 CFR Part 1065, Part 86, and Part 1039. It should also be noted that, in general, SwRI worked to keep carbon balance for Dilute and Raw

emission measurements within the recommended 2% level, although this was not always maintained on some of the tests using some of the prototype Low NO_X AT systems. Even when maintained within the recommended 2% range, this still allowed for variation over time and among systems. In order to enable meaningful comparison of CO_2 emission results over the long performance periods and multiple systems of this program, tailpipe CO_2 emission results were corrected to place them on the same carbon balance basis as the baseline emission results. The approach to this is detailed later under the results section of the report.

2.3 Test Cycles, Test Procedures, and Preconditioning Procedures

The targets for this program were demonstrated over the relevant on-road regulatory cycles, including the NRTC, RMC, and the LLAC that was developed during the previous Stage 1 effort under CARB Contract 18RD006.

For the baseline and final demonstration tests, all tests were run in triplicate. The demonstration test sequence was as follows:

- One cold-start NRTC test
- 20-min engine-off soak
- Three successive hot-start NRTC tests (with a 20-min engine-off soak between tests)
- 20-min engine-off soak
- One LLAC
- One RMC (containing its own preconditioning which is another RMC run directly before the test for record with no dwell between cycles)

All testing and preconditioning was conducted in accordance with the procedures given in 40 CFR Part 1039 and 40 CFR Part 1065.

The NRTC and RMC cycles are well documented in 40 CFR Part 1039, and are currently used for certification of Tier 4 engines. For this program we are using the 8-mode RMC cycle designated for variable speed engines. The LLAC cycle, on the other hand, was developed specifically to represent lower load operations, as described above. The LLAC is depicted in Figure 7. below. A comparison of the average power of all of these cycles, in comparison to each other and the on-road cycles is given in Table 2.

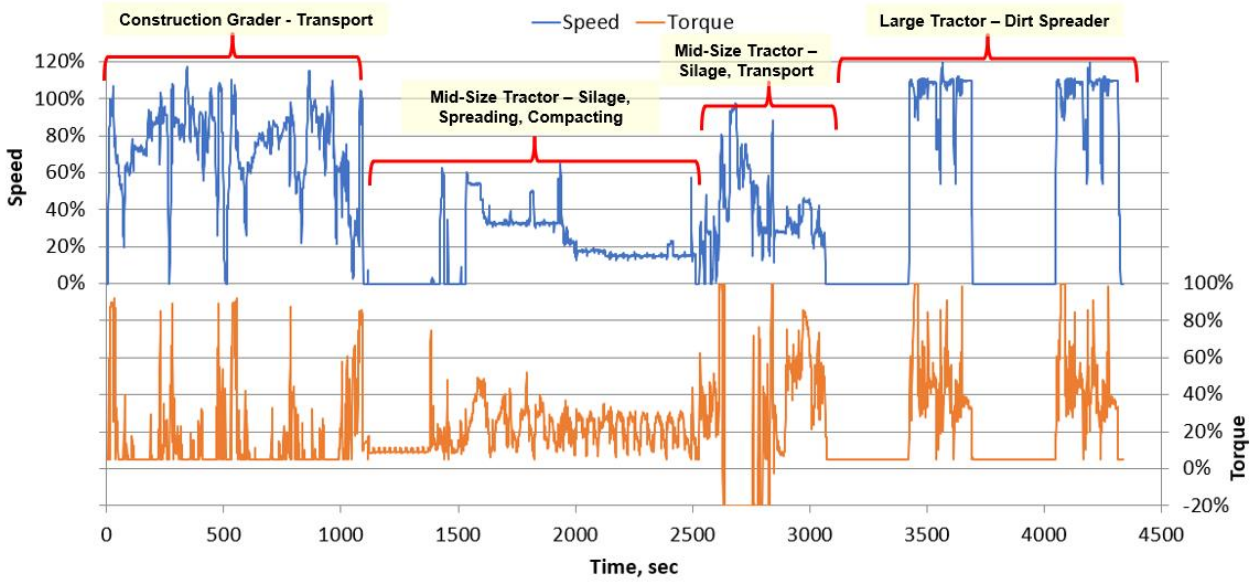


FIGURE 7. OFF-ROAD LOW LOAD APPLICATION CYCLE (LLAC)

TABLE 2. CYCLE AVERAGE POWER FOR COMPLIANCE CYCLES

Operation	On-Highway		Off-road	
	Cycle	%Max Power	Cycle	%Max Power
Transient	FTP	22 %	NRTC	37 %
Steady-State	RMC-SET	48 %	RMC	55 %
Low Load	LLC	6 – 7 %	LLAC	15 %

Preconditioning for the NRTC cycle involved two NRTC transient hot-start tests, with a 20-minute soak between the two tests, as outlined in 40 CFR Part 1065. The engine was then placed in overnight cold-soak. Operations prior to the preconditioning NRTC tests were not specified, but if a DPF regeneration was needed it was run prior to the start of the preconditioning NRTCs. It was found that operations prior to the preconditioning NRTCs did not have any impact on the result of the NRTC tests. The emission control system was designed and tuned to reach emissions stability with the NRTC duty cycle after two NRTC preconditioning tests.

Preconditioning for the RMC was conducted as outlined in 40 CFR Part 1065, wherein an RMC cycle is run immediately prior to the start of the RMC test for record. The preconditioning and test cycles were run head-to-tail, with no dwell between the end of the preconditioning cycle and the start of the test for record.

Preconditioning for the LLAC was selected to be analogous to the approach developed for the on-road LLC, and involved running at least one hot-start NRTC. If the test sequence is run as described above, the final NRTC hot-start test of the NRTC test sequence serves as preconditioning

for the LLAC, such that no additional engine operation is needed, and the LLAC can be run following a 20-minute soak. However, in the event the sequence was interrupted, a preconditioning hot-start NRTC would be run, followed by a 20-minute engine-off soak and then the LLAC test itself.

2.4 Low NO_X Aftertreatment Hardware

Advanced AT hardware for this program was supplied in kind by members of the Manufacturers of Emission Controls Association (MECA). The MECA suppliers for this program self-organized into two supplier teams, each consisting of a catalyst company, substrate supplier and canning company. Each team was supplied a set of data from SwRI to aid in system design and simulation. These data sets were taken from SwRI engine calibration efforts and projections of expected performance from technologies like CDA. The supplier teams used this data to develop two sets of AT technology offerings, each with several optional elements. This approach provided SwRI with a wide variety of technologies to choose from in developing a final AT system approach to reach the NO_X and CO_2 goals of the program. It was understood that these systems were developed with the intention of reaching a 12,000 hour FUL.

Initial simulations from the previous program effort under 18RD006 indicated that it might be feasible to reach program targets, at least for Package 1, using a more conventional AT system architecture, as depicted in Figure 8. Later modeling work from the suppliers indicate similar results, and therefore Package 1 system designs reflected this. On the other hand, depending on the final engine-out NO_X level for Package 2 chosen in trying to reach the CO_2 reduction targets, Package 2 might require a more complicated architecture. Therefore, an option to use light-off SCR (LO-SCR) technology and dual diesel exhaust fluid (DEF) dosing was also procured. In addition, several hardware options were also procured for the systems, including heated dosing, electric heaters (e-heater), and an electrically heated mixer. Given that these options are more related to pursuit of further GHG reductions, they will likely be evaluated in the following program work under 20MSC005.

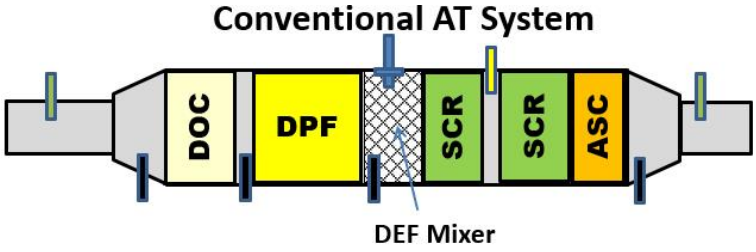


FIGURE 8. CONVENTIONAL AFTERTREATMENT SYSTEM ARCHITECTURE – DOC+DPF+SCR

Individual AT system options are described in more detail in the report sections below.

2.4.1. Aftertreatment Team 1

Aftertreatment Team 1 supplied a system primarily designed for Package 1 usage, although it could be utilized for Package 2 with the optional added volume if sufficient performance and durability reserve are observed. The Team 1 system was a conventional architecture having a

DOC+DPF+SCR arrangement. The system was designed as a single inline module featuring a "compact mixer" design and a production style side-inlet cone. The base system design, originally intended for 8,000-hour useful life had two 12x4 inch SCR bricks, the second of which had 2 inches of ASC coating on the back. This system is depicted below in Figure 9.

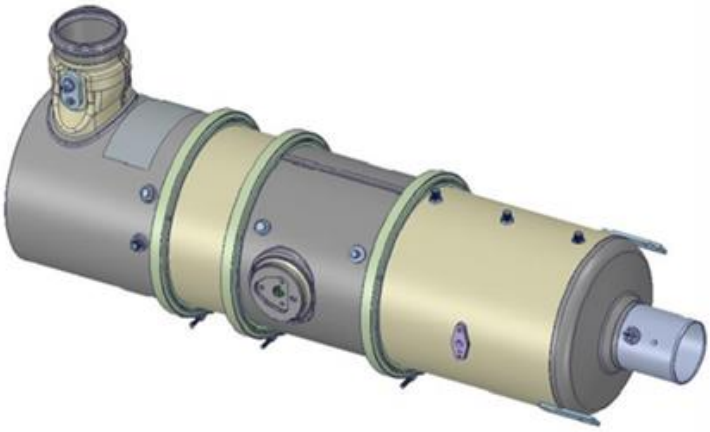


FIGURE 9. TEAM 1 AFTERTREATMENT PRIMARY CONCEPT FOR PACKAGE 1

More detail about the catalysts is given below in Table 3. The system was also designed to allow the installation of a third 12x4 inch SCR brick to ensure sufficient durability reserve for 12,000 hours of aging. This same arrangement could also be potentially used as a Package 2 candidate, although that is not the original intent. The actual system is shown in Figure 10 in the Package 1 arrangement without the additional 4-inch SCR brick installed.

TABLE 3: TEAM 1 CANDIDATE AFTERTREATMENT SYSTEM CATALYST SPECIFICATIONS

Component	D x L, in	CPSI/Wall, mm	Volume
DOC	12x4	400/4	8.3 L
DPF	12x4.7	300/7	8.7 L
SCR[1]	*12x4*	*600/4.5*	*7.5 L*
SCR	12x4	600/4.5	7.5 L
SCR-ASC	12x4	600/4.5	7.5 L
[1] If necessary for 12k hours or Package 2			



FIGURE 10. TEAM 1 CANDIDATE AFTERTREATMENT PACKAGE 1 CONFIGURATION

The system was designed to mount a conventional Bosch Denoxtronic 2.2 DEF injector with a 6-hole configuration.

2.4.2. Aftertreatment Team 2

AT Team 2 also designed their system around a single inline module approach. Team 2 also provided two different options for the portion of the catalysts system before the post-DPF DEF injector. The first option was designed for use on Package 1, and potentially Package 2 if performance was sufficient. This system is depicted below in Figure 11, shown with the third (again optional) 12x4 inch brick installed upstream of the other two SCR bricks.

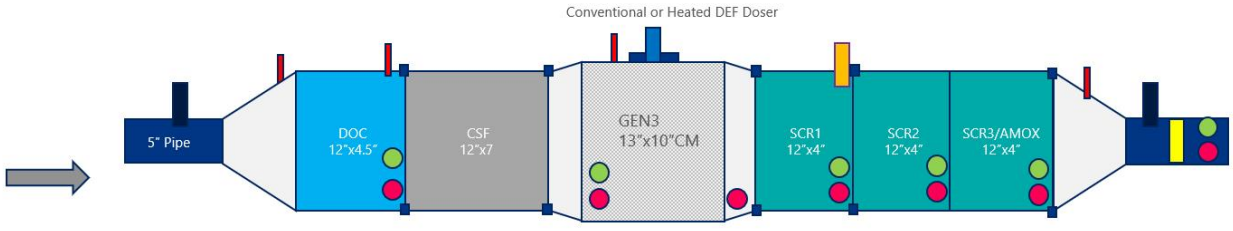


FIGURE 11. TEAM 2 AFTERTREATMENT CONCEPT – 12,000 HOUR VERSION

TABLE 4. CATALYST SPECIFICATIONS FOR TEAM 2 CONVENTIONAL ARCHITECTURE SYSTEM

Component	D x L, in	CPSI/Wall, mm	Volume
DOC	12x4.5	400/4	8.3 L
DPF	12x7	300/7	13 L
SCR[1]	*12x4*	*600/4.5*	*7.5 L*
SCR	12x4	600/4.5	7.5 L
SCR-ASC	12x4	600/4.5	7.5 L
[1] If necessary for 12k hours or Package 2			

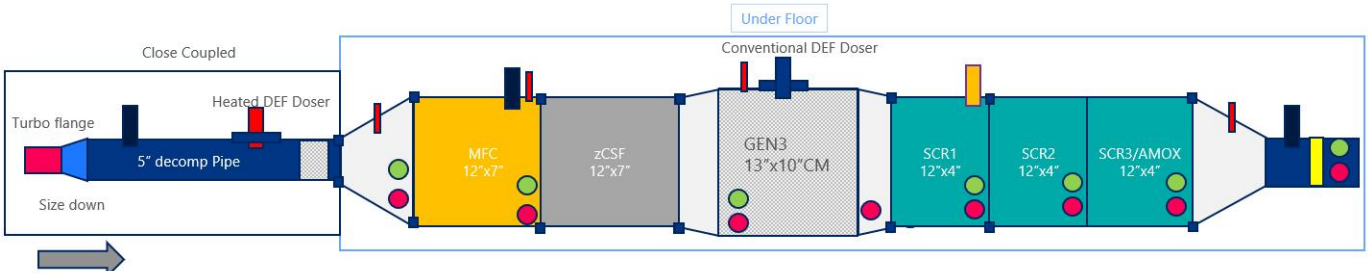


FIGURE 12. TEAM 2 AFTERTREATMENT CONCEPT FOR PACKAGE 2 WITH DUAL SCR DUAL DOSING ARRANGEMENT

TABLE 5. TEAM 2 CATALYST SPECIFICATIONS FOR DUAL-SCR DUAL DOSING ARCHITECTURE SYSTEM

Component	D x L, in	CPSI/Wall, mm	Volume
MFC (LO-SCR))	12x7	400/4	13 L
Zone-coated CSF	12x7	300/7	13 L
SCR[1]	*12x4*	*600/4.5*	*7.5 L*
SCR	12x4	600/4.5	7.5 L
SCR-ASC	12x4	600/4.5	7.5 L
[1] If necessary for 12k hours or Package 2			

2.5 Low NO_X Engine Hardware Options

2.5.1. EGR Cooler Bypass

To alleviate concerns of hydrocarbon (HC) condensation within the EGR cooler, which can lead to fouling, the base engine calibration does not use EGR below 1200 rpm engine speed. However, no EGR operation increases engine-out NO_X and exhaust flow rate which can accelerate AT cooling. To address these issues, an EGR cooler bypass was implemented on the test engine. The stock EGR transfer elbow located before the high-pressure turbine was modified to provide hot exhaust gas, which was controlled with an electronically-controlled wastegate, before being

introduced downstream of the stock EGR valve. Photos of the EGR cooler bypass implementation are shown in Figure 13. Test results obtained with the EGR cooler bypass will be discussed in the results section.

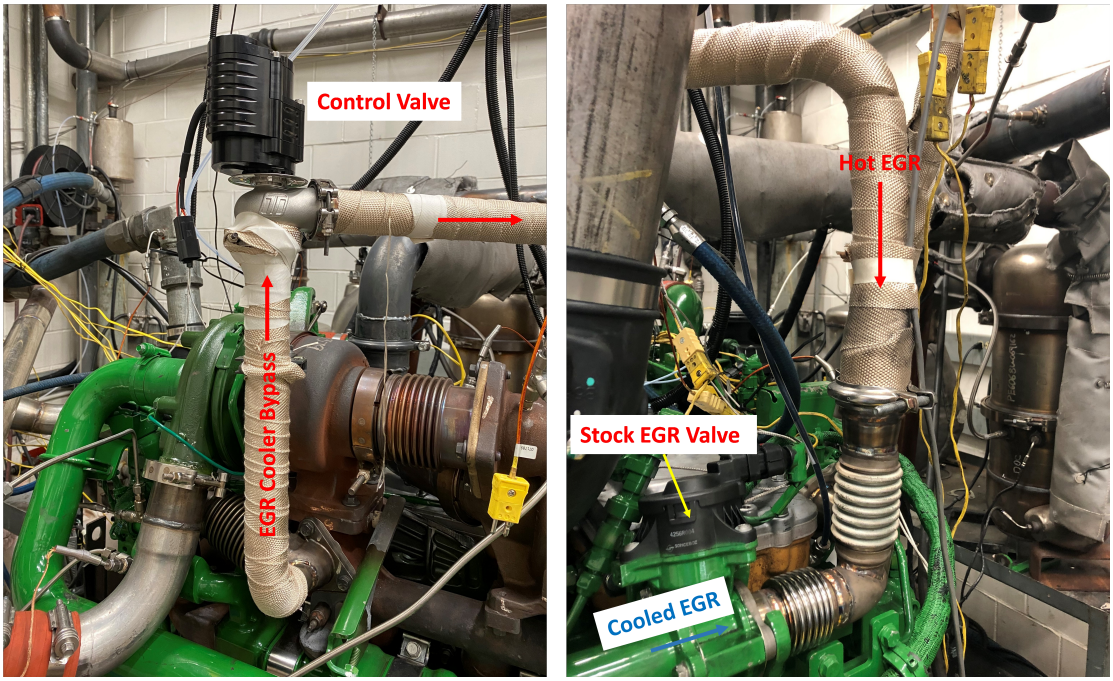


FIGURE 13. EGR COOLER BYPASS IMPLEMENTATION

2.5.2. Cylinder Deactivation (CDA)

Another major hardware lever evaluated for inclusion in Package 2 was CDA.[6][7] This was a primary technology leveraged in the on-road Low NO_X effort, and was also evaluated here for application to the off-road market. It should be noted that due to the significant differences between on-road and off-road, it was necessary to re-evaluate whether CDA would continue to provide enough value to justify the cost and effort to deploy the technology.

The CDA system hardware used in this program was supplied by Jacobs Vehicle Systems (JVS). The system is shown below in Figure 14, installed on the Deere 6068 engine. As can be seen in the figure, there is an individual control solenoid for each cylinder, allowing independent deactivation of any or all cylinders. This allowed maximum flexibility for any CDA strategy, as well as enabling the use of diesel Dynamic Skip Fire (dDSF) algorithm, as discussed below. The system was controlled via the dSPACE MicroAutobox II (MAB2) integration controller that was deployed by SwRI, using software that was developed working with Jacobs Vehicle Systems (JVS) for control, and a solenoid driver system developed by SwRI for this application.

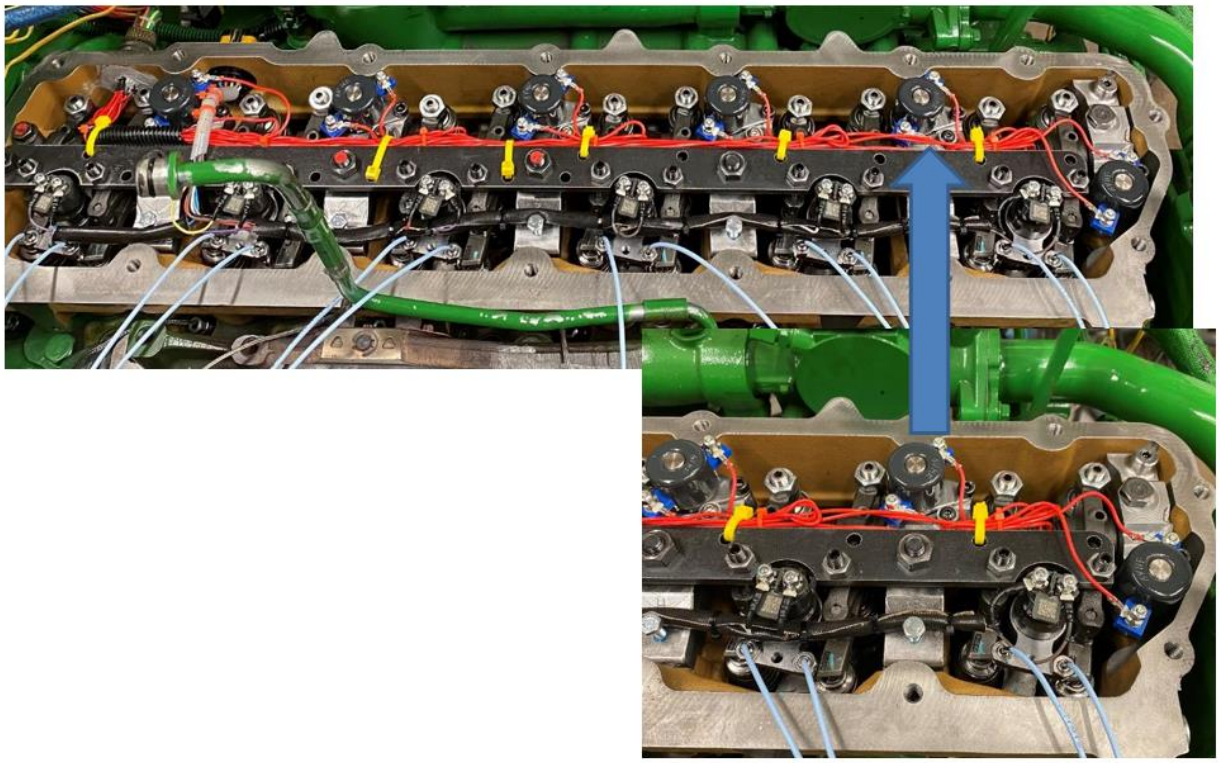


FIGURE 14. CYLINDER DEACTIVATION SYSTEM (JACOBS VEHICLE SYSTEMS)

2.5.3. Diesel Dynamic Skip Fire (dDSF™)

A further innovation in the control of CDA hardware technology is the use of a more flexible control architecture developed by Tula Technology which is known as Diesel Dynamic Skip Fire (dDSF). Rather than utilizing a strategy which moves between fixed modes of CDA operation, dDSF uses a more sophisticated algorithm to continuously vary the number of cylinders being operated at lighter load. An illustration of how this concept works is given below in Figure 15.[8] The use of dDSF can enable a wider range of more frequent cylinder deactivation under transient cycles, thus enabling a larger benefit than map-based CDA. In addition, dDSF can be used to avoid noise, vibration, and harshness (NVH) resonances in more dynamic fashion, thus enabling CDA to be used more readily in areas that might otherwise be limited in flexibility due to vibration limits.

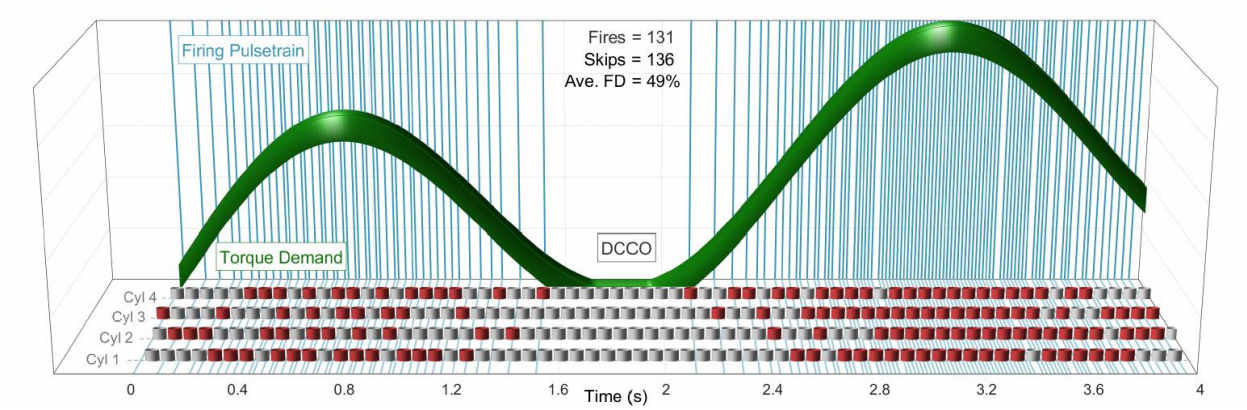


FIGURE 15. ILLUSTRATION OF DYNAMIC SKIP FIRE (FROM TULA PRESENTATION AT 9TH INTERNATIONAL ENGINE CONGRESS, BADEN-BADEN, GERMANY)

2.6 Low NO_X Controls

A significant portion of the effort in the Low NO_X demonstration program involved the development of the hardware and software controls needed to make the combined engine-AT system function, and to provide the flexibility needed to minimize tailpipe NO_X and maximize engine efficiency. Although the controls were implemented in an open development platform, the controls used on the off-road Low NO_X engine were designed using a production-oriented approach based on SwRI's experience working with production engine controls. As with a production controller, a single unified strategy and calibration were developed that could run on any duty cycle without cycle specific tuning.

The basic control architecture for this program is shown in Figure 16. The core strategy and much of the custom controls were operating from the SwRI Controller, which resided in a dSPACE MAB2 platform. The controller hardware itself is shown in Figure 17. The SwRI Controller had overall supervisory control of the system, and several key controls were located there. These included the Engine State Machine, the main CDA controller, and the AT Controller.

The SwRI Controller was linked to the engine via a proprietary link allowing the SwRI controller to override various engine functions and operating modes as needed to implement the Low NO_X strategy. John Deere also provided proprietary tools to enable ECM calibration access, as well as provided calibration engineering support to the program for areas that would have been too complicated for SwRI to make adjustments directly.

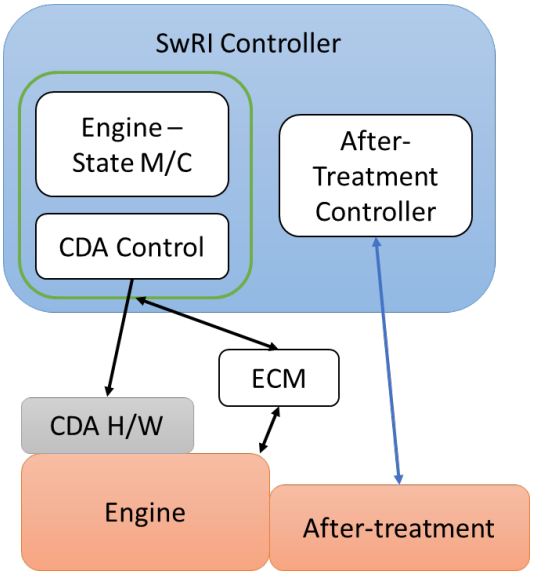


FIGURE 16. HIGH-LEVEL CONTROL STRUCTURE FOR LOW NO_X DEMONSTRATION

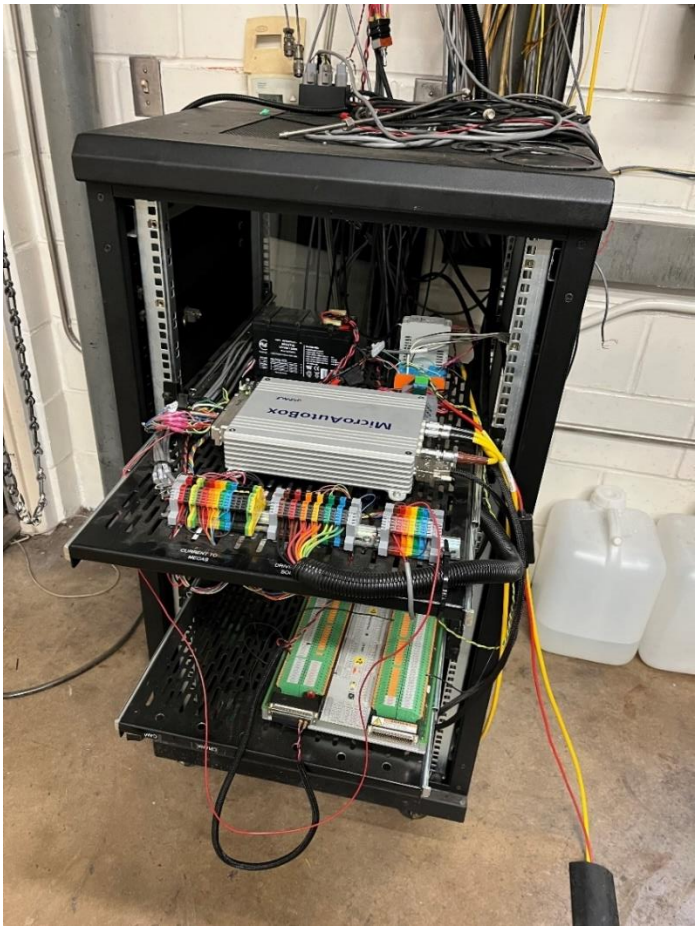


FIGURE 17. LOW NO_X INTEGRATION CONTROLLER HARDWARE PLATFORM

2.6.1. Overall Strategy and Engine State Machine

The Engine State Machine contained the primary strategy controls for the engine-AT system. The strategy control was implemented a series of engine modes that allowed the implementation of different calibration targets, depending on the state of the system. This strategy was driven by a combination of Engine Coolant Temperature (ECT) and AT system temperatures. In particular, the temperature of the first brick of the SCR system (SCR1 in the diagrams) were used to drive state switching. The strategy is shown in Figure 18 and involved three primary engine states that were defined as follows:

- **Fuel Economy (FE)** – this mode was the desired endpoint of the strategy and can be considered the "Default" operating mode when the engine and AT system are at optimal temperatures for maximum NO_X efficiency. It has the highest engine-out NO_X emissions and the lowest CO_2 emissions. In some cases, this mode actually was calibrated to higher engine-out NO_X levels than the baseline engine.
- **Aggressive Thermal Management (TM-1)** – this mode was used when both catalyst beds were below optimal temperature, and represents the most aggressive thermal management mode used outside of cold-start. TM-1 had the lowest engine-out NO_X level and the highest CO_2 emissions. Features of this mode included higher EGR rates, significant use of multiple injections, combustion phasing, intake throttling, and modifications to the CDA mode table that prioritized system temperature at certain speeds. Due to the impact on CO_2 this mode was used only to the degree necessary.
- **Low Thermal Management (TM-2)** – this mode was a transitional mode that was added to provide an intermediate point between FE and TM-1. This was used in cases where the AT system temperatures were at temperatures slightly below optimal, but still able to reach high conversion on at least one of the catalyst beds. TM-2 provided a less drastic mode of intervention allowing moderate thermal management and some NO_X reduction, but with significantly less CO_2 penalty than the TM-1 mode. The flexibility added by TM-2 was essential for optimizing CO_2 emissions in part load duty cycles.

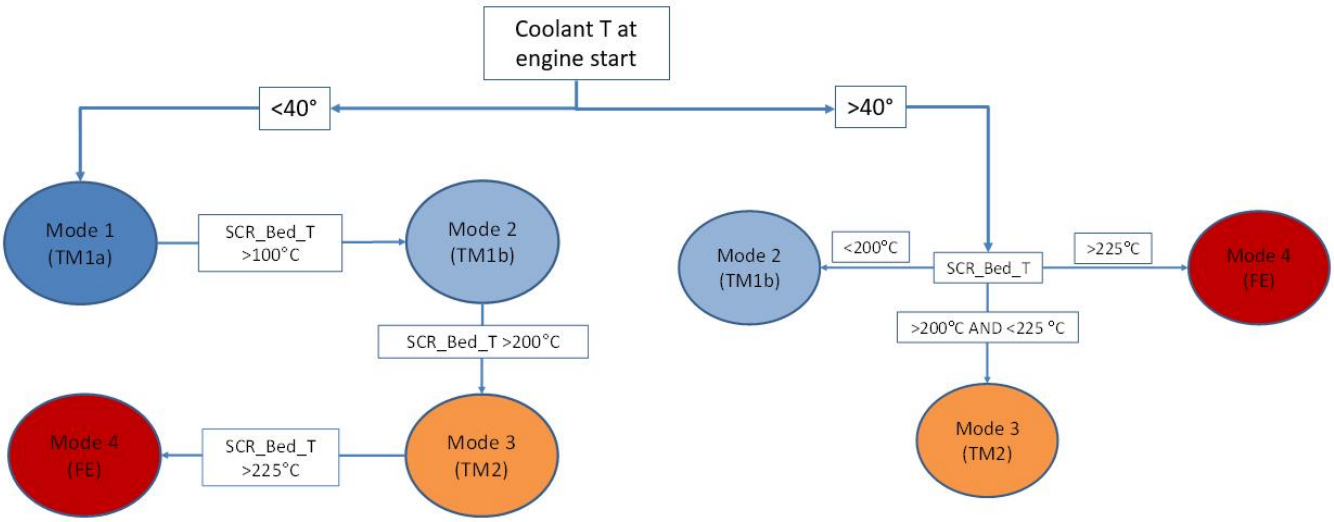


FIGURE 18. ENGINE STATE MACHINE AND OVERAL STRATEGY CONTROL DIAGRAMS

Under normal operations after engine-start and when ECT was above 40°C, these three modes were the only active modes, and the strategy work cycle between these modes was dictated by the AT system temperatures. Each of these modes was tied to a set of maps in the engine ECM for various systems, leveraging the existing controls within the engine ECM as much as possible. SwRI then recalibrated these maps to implement the desired strategy.

If at engine start the ECT was below 40°C, additional sub-modes (engine mode TM1a in Figure 18) was enabled under the TM-1 mode to implement early stages of the cold-start warmup strategy. Transition out of these modes was based on ECT and the SCR temperature, given that the primary purpose of these modes was to warm up the SCR as rapidly as possible. An example of the control switching over a cold-start NRTC is shown in Figure 19 below. A different duty cycle during cold-start would likely result in a different progression through these modes, as would different ambient conditions, and an example of this behavior over a different cold-start duty cycle with a much longer initial idle is shown later in the results section.

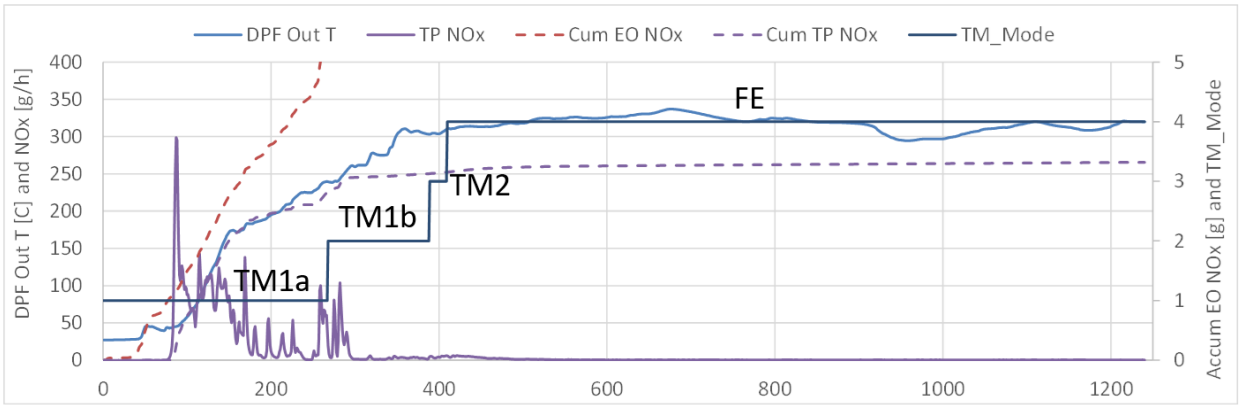


FIGURE 19. EXAMPLE OF CONTROL MODE SWITCHING DURING COLD NRTC

Additional specialized controls modes were also implemented for specific functions, such as DPF Regeneration or SCR de-sulfation ($deSO_X$). DPF regeneration also involved control of post injection via the Deere ECM. More discussion on the strategy associated with these modes is given under the AT Controls section. Due to scope limitations, these specialized modes were not fully calibrated for transient cycle implementation as part of this demonstration program.

2.6.2. Aftertreatment Controller and DEF Dosing Controls

The SCR sub-controller is depicted in Figure 20, and the basic control structure is shown in Figure 21. This system was patterned of the controller used for the downstream SCR system under the on-road Low NO_X program.[2]

As shown in Figure 21, the dosing command is the sum of corrections for both the first SCR bed (SCR1) which is before the NH_3 sensor, and the second SCR bed (SCR2) after the NH_3 sensor, with each bed having both an average storage correction, and a profile-based correction. However, the two beds target a different desired profile, given that the first bed must provide ammonia to the second bed, while the second bed profile is targeted to avoid tailpipe NH_3 slip. A further bias function is used to help drive coverage to desired levels by allowing the first bed to exceed its targets in cases where the second bed is too far below targets. The SCR catalyst controller also contains a deposit avoidance limiting of maximum dosing and an accelerated dosing feature to help quickly recover ammonia coverage when the model sees that the storage is far below the target levels.

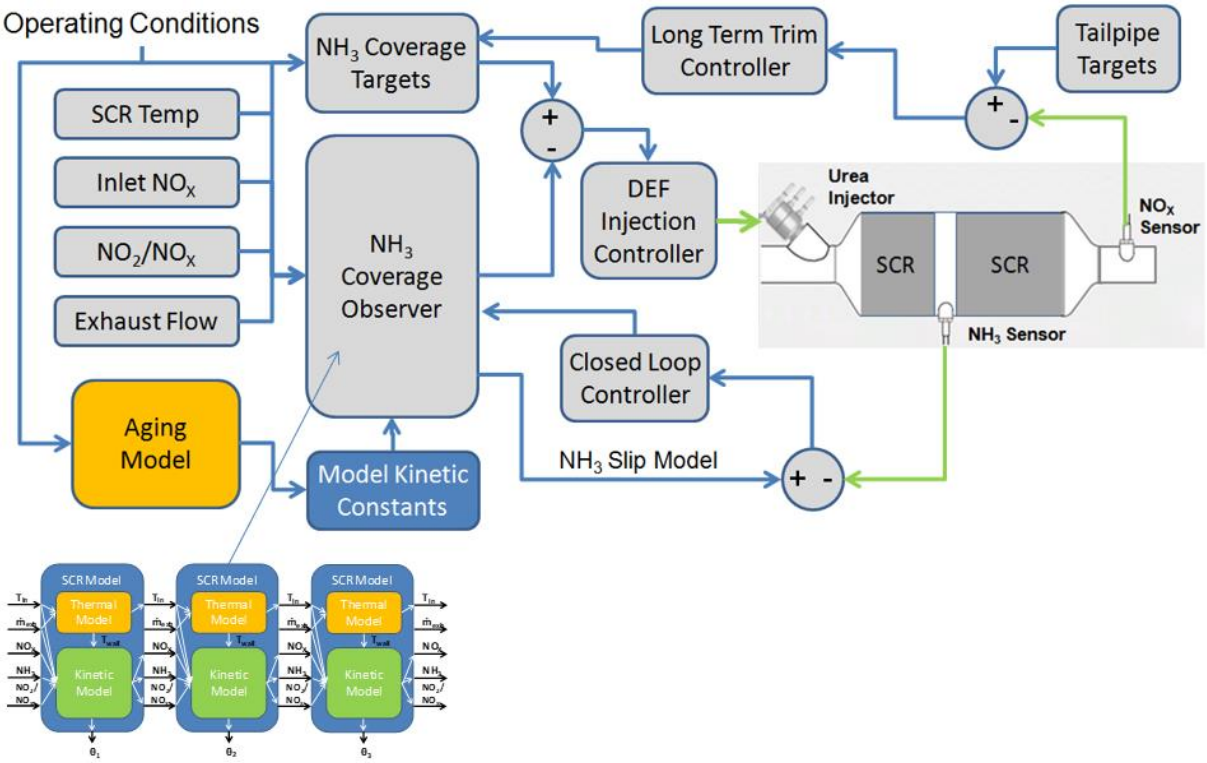


FIGURE 20. PRIMARY SCR DOSING CONTROLLER SCHEMATIC

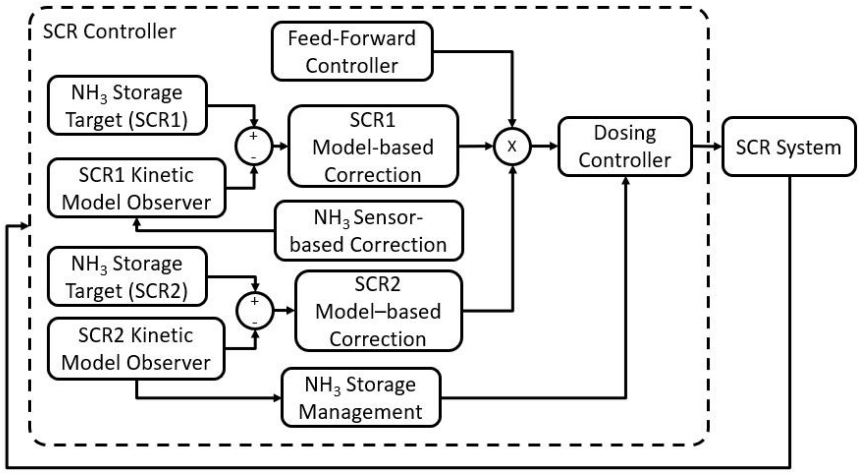


FIGURE 21. PRIMARY SCR CONTROLLER STRUCTURE

The primary added feature was the high-speed feedback element, driven by the mid-bed NH_3 sensor. To meet tailpipe NO_X targets and in-use requirements, the warmed up AT system must be able to maintain NO_X conversion in excess of 99.5%. Given even a small margin for degradation of 0.25%, this translates to a controls demand to be above 99.75% conversion consistently before any degradation. From a control standpoint, maintaining such a high performance level consistently requires a high amount of precision, and it is very difficult to maintain that kind of precision on any system without some form of real-time feedback. Slower long-term trim adjustments, while also important for long-term precision are not enough by

themselves. For the model-based DEF controls, the key parameter modeled is ammonia storage, and therefore some real-time feedback element is needed that can provide information about how accurate the storage model actually is. Either NO_X or NH_3 could be used for this purpose. However, the tailpipe NO_X sensor cannot be used for this function because the SCR catalysts itself is such a large filter that any tailpipe sensor signal, whether NO_X or NH_3, is simply too slow to be of use. A tailpipe NH_3 sensor would have a similar attenuation problem, in addition to the fact that tailpipe NH_3 levels are generally low, and the presence of the ASC would eliminate most of the remaining signal.

For this reason, the catalyst was split into two regions with a mid-bed sensor to provide feedback. At this location a mixture of both high NO_X and high NH_3 is expected, therefore a NO_X sensor would not be useful due to the cross-sensitivity of currently available sensors. Therefore, a mid-bed NH_3 sensors was the only viable option for real-time feedback. However, the currently available production NH_3 sensor is known to have issues with accuracy at lower NH_3 levels (below 30ppm), and is also subject to significant drift over time. It was necessary to use the NH_3 sensor in a manner that was not sensitive to these issues. As shown in Figure 20 above, the mid-bed NH_3 sensor was used for model state correction based on comparison to the model predicted value at the mid-bed location. Because the NH_3 sensor is used as a state sensor (i.e. to detect an NH_3 grossly rich condition or the absence of NH_3 or the rapid transition between such states), rather than in a traditional feedback loop, the absolute accuracy of the NH_3 sensor is not as important, and the sensor functions primarily to detect the presence of an unexpected ammonia wave, or the absence of a predicted ammonia "wave." This allows the feedback algorithm to correct storage over a timescale of seconds to minutes, and the more accurate storage prediction allows the controller correct catalyst behavior better. This strategic use of the NH_3 sensor signal relies on wide rapid swings in NH_3 concentration inherent to the aftertreatment system design such that the NH_3 "wave" event indication timing is relatively insensitive to zero offsets and typical variation in sensor gain.

Figure 22 shows an example of how the ammonia storage profiles look during a typical hot-start NRTC. Storage is tracked in the model as the variable "theta," which is a fractional ratio of ammonia storage compared to the maximum capacity of the system at a reference condition of 200°C. As temperature increases, this coverage ratio (theta) can be seen to drop exponentially. For each catalyst both the actual (black) and target (red) average storage values are shown, along with the actual coverage values for each of the seven model cells on a given bed. As can be seen in the figures, the individual cell coverage values can be very dynamic, and they illustrate how storage evolves through a given catalyst bed over time. This profile information can be very useful for high efficiency SCR control, as it can be used to spot a wave of ammonia moving through the catalyst, allowing controls to react to that profile to prevent ammonia slip before it occurs, while also maximizing coverage and preparing the next wave of ammonia. In this way, the controls can be thought of as arranging a succession of waves of ammonia to pass through the catalysts as the temperature cycles.

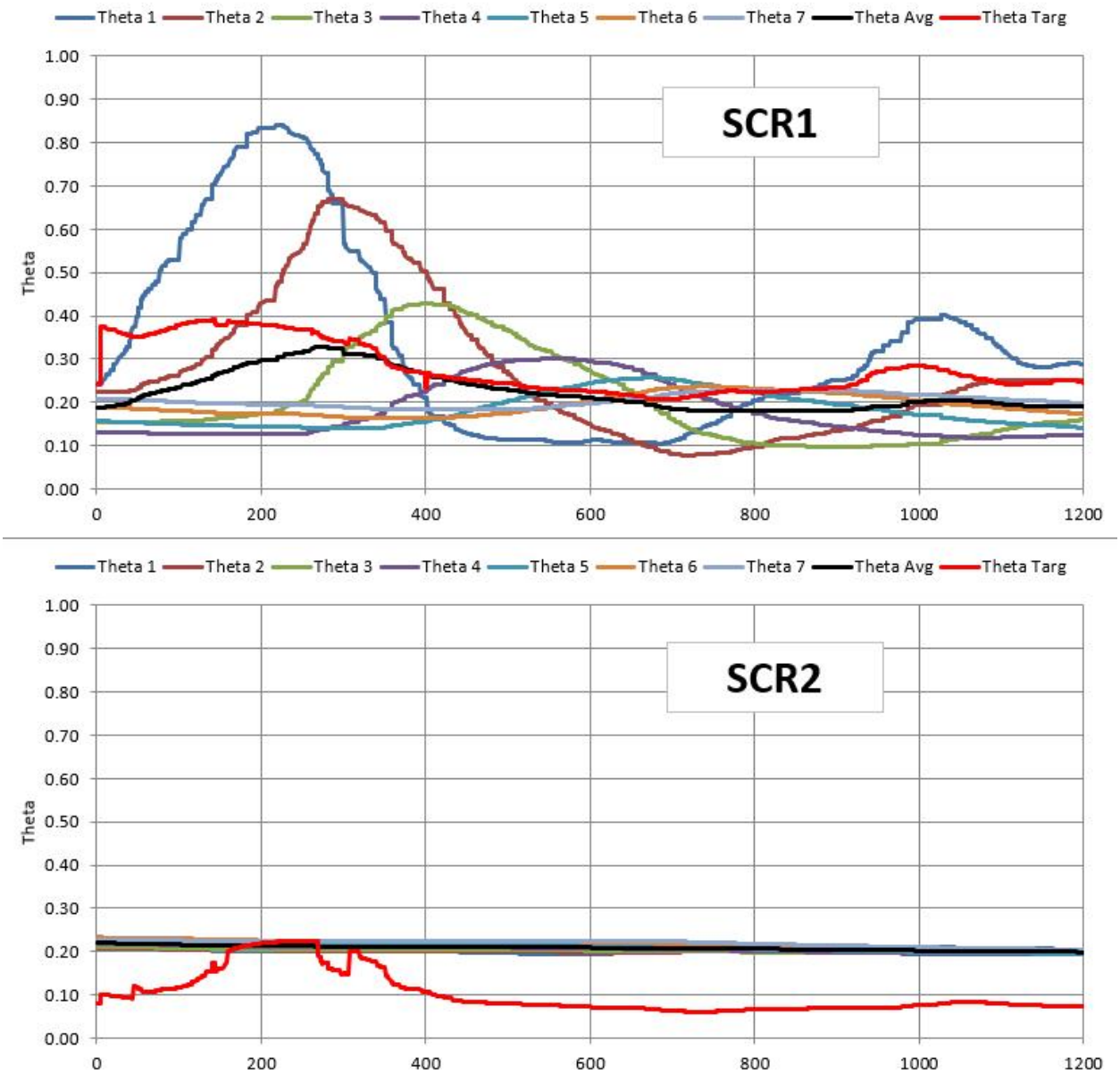


FIGURE 22. EXAMPLE OF AMMONIA STORAGE PROFILES DURING HOT-START NRTC CYCLE

2.6.4. Overall Aftertreatment System Control Strategy

The DEF dosing controls described above allow for a great degree of flexibility in designing a strategy to manage the usage of the SCR catalysts systems to try to reach the program targets for NO_X and CO_2 in a robust manner. At the same time, other system priorities, such as removal of soot from the DPF, must also be considered. The planned strategy was considered at the time of the AT hardware design, and implemented in the calibration of the DEF dosing controls and the engine state machine thermal states.

Under cold-start warm-up conditions, stored ammonia on the surface of the catalysts is crucial to maximizing performance during catalyst light-off. Although the lower temperature capability of the heated dosing is helpful in this case, the high storage capacity of the zeolite SCR catalysts at low temperatures makes it difficult to push enough ammonia through the catalysts to achieve coverage. Therefore, previously stored ammonia is vital for reaching Low NO_X levels during cold-start which creates a design aim to continuously maintain target coverage prior to each (time-unknown) engine shutdown. A significant amount of the strategy is designed to enable rapid recovery of SCR storage that will be needed for the next start event. The accelerated dosing modes of the controller and the low deposit risk, high DEF dosing rate capabilities of the heated dosing system are both important features for this to work on an optimal fashion over a wide variety of duty cycles and entry conditions.

2.7 Aging Methodology – Development Aging (Hydrothermal Only)

The Development Aging process was designed to simulate of FUL of hydrothermal aging only. The process did vary slightly from one set of hardware to the other, given that there were some differences in key parameters like Active Regeneration target temperature. The basic approach to Development Aging was to leverage the exponential relationship of temperature and thermal deactivation, but without the extra time for the chemical poisoning elements of the full DAAAC aging protocol [9][10] that will be used later under 20MSC005. In effect, all of the high temperature exposure events were collected together, with little or no time in between. Because the final systems were not yet developed, conservative choices were made regarding regeneration durations and frequencies.

Development Aging was conducted on the ECTO-Lab burner system, illustrated in Figure 23. This system allows the simulation of exhaust conditions of many different engines, and can be used for aging and evaluation of full-size engine AT systems for engines ranging from 3-15L in displacement.

For Package 1 which utilized the conventional DOC+DPF+SCR architecture, the estimated regeneration frequency used to scale aging was 45 minutes every 80 hours, which is equivalent to the baseline engine regeneration frequency. This worked out to 113 hours of total regeneration over the course of 12,000 hours of operation. A conservative target temperature of 600°C at the DPF was chosen for the development aging. This temperature is higher than the 565 to 575°C temperature typically seen for off-road DPF regenerations, but was selected primarily due to experience on the on-road Low NO_X program. This was due to the earlier success in that program controlling long-term sulfur poisoning at these temperatures. It is possible that a lower temperature would be successful for deSO_X, but for Development aging early in the program, the conservative higher temperature was used to avoid under-prediction of aging for the purposes of comparing technologies to each other. A DOC inlet temperature of 350°C was used, and then the target

temperature was reached using HC injection over the DOC, as would be the case in the real application.

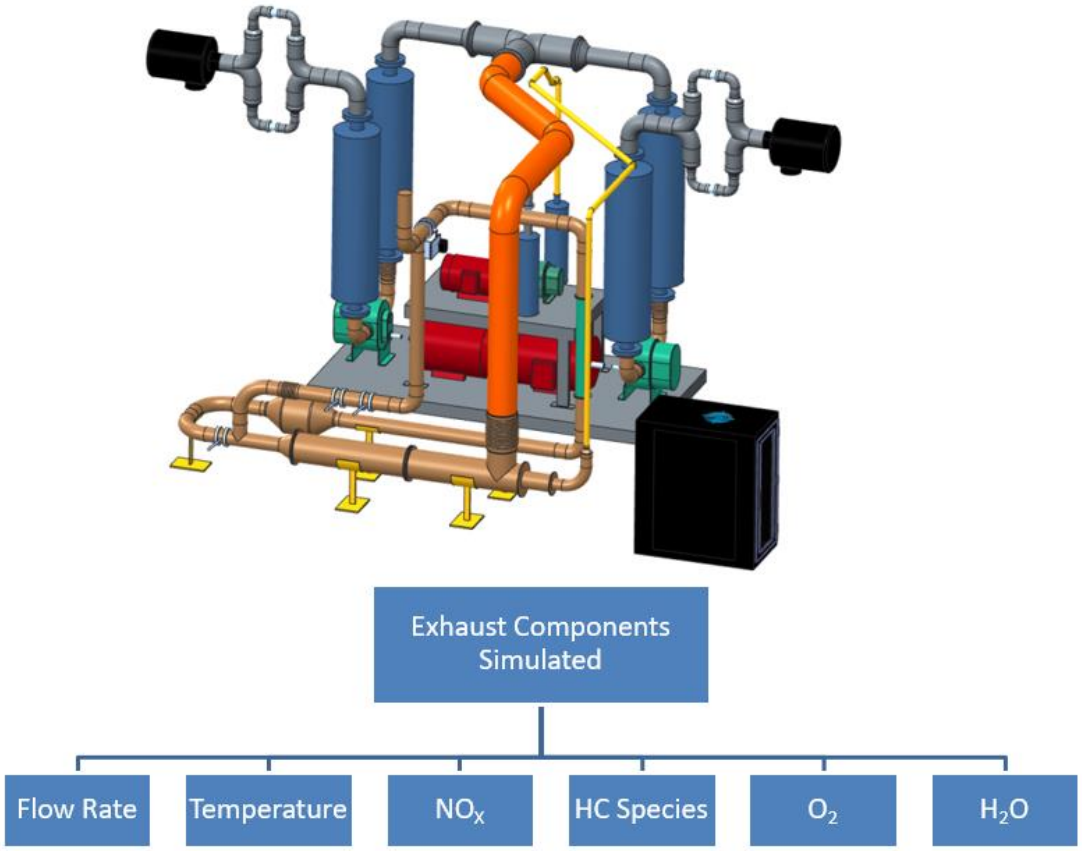


FIGURE 23. SWRI ECTO-LAB™ BURNER-BASED AGING AND TEST STAND

This approach was used for all systems except the Team 2 LO-SCR (MFC) option. In this case, a lower target temperature of 575°C was used for two-thirds of the time as a result of the different configuration, but temperature of 600°C was used one-third of the time to represent an end of regeneration kick up temperature that would be used to remove any residual sulfur still stored on the downstream SCR.

3.0 RESULTS AND DISCUSSION

3.1 Baseline Engine Testing

With a nominal power rating of 187 kW, the 6.8L John Deere 6068 engine complied with Tier 4 Final emission standards for the following power rating specification category: 130 ≤ kW ≤ 560. Emission standard information is shown in Table 6 and includes the additional EPA guidance for NH_3 emissions (not regulated).

TABLE 6. TIER 4 FINAL CRITERIA EMISSION STANDARDS: 130 ≤ KW ≤ 560

	Tier 4 Final Emission Standards [g/kW-hr]				
	NO_X	PM	NMHC	CO	NH_3
Standard	0.40	0.02	0.19	3.5	< 10 ppm average

Baseline engine out and tailpipe emission results are shown in Table 7 and Table 8. The values reflect the averages based on three (3) replicates completed for each cycle. NRTC composite results were calculated based on cold start cycle weighting of 5% and a hot start cycle weighting of 95%, as given in 40 CRR 1039.510(b). In addition to CO_2 and the criteria emissions, brake specific PN results were also reported for the tailpipe measurements only.

Figure 24 shows reported brake specific CO_2 results from the tailpipe location. The NRTC cold and hot start cycle composite resulted in an average of 748 g/kW-hr, while the RMC cycles were lower by ~ 6.7%. The LLAC was reported with a relatively high CO_2 value at 835.8 g/kW-hr, which also indicated higher brake specific fuel consumption. Overall, results were consistent between replicates, with the highest coefficient of variation (COV) at 0.5%.

TABLE 7. JOHN DEERE 6.8 L BASELINE ENGINE-OUT EMISSIONS RESULTS

			NRTC							
			Cold	Hot 1	Hot 2	Hot 3	Composite	Hot-Avg	LLAC	RMC
Average	THC	g/kW-hr	0.11	0.08	0.10	0.10	0.08	0.09	0.19	0.07
	NMHC	g/kW-hr	0.11	0.10	0.07	0.10	0.10	0.09	0.19	0.06
	CO	g/kW-hr	1.2	1.0	1.0	1.0	1.0	1.0	1.3	0.4
	NOx	g/kW-hr	3.1	3.0	3.0	3.0	3.0	3.0	5.3	3.1
	PM	g/kW-hr	0.11	0.11	0.10	0.10	0.11	0.10	0.10	0.04
	CO2	g/kW-hr	760.3	745.5	745.0	744.5	746.2	745.0	830.3	698.1
	Work	kW-hr	23.88	23.79	23.77	23.76	23.8	23.77	34.60	51.69
Stdev	THC	g/kW-hr	0.0021	0.0019	0.0029	0.0019	0.0017	0.0022	0.0049	0.0006
	NMHC	g/kW-hr	0.0021	0.0024	0.0021	0.0018	0.0022	0.0021	0.0048	0.0006
	CO	g/kW-hr	0.0078	0.0138	0.0139	0.0095	0.0134	0.0119	0.0109	0.0015
	NOx	g/kW-hr	0.0096	0.0034	0.0076	0.0058	0.0035	0.0036	0.0188	0.0097
	PM	g/kW-hr	0.0045	0.0101	0.0101	0.0196	0.0093	0.0125	0.0051	0.0077
	CO2	g/kW-hr	1.10	0.66	1.18	1.33	0.68	1.04	1.56	0.52
	Work	kW-hr	0.003	0.008	0.004	0.009	0.008	0.007	0.029	0.01
COV	THC	%	1.9%	2.4%	2.8%	1.8%	2.1%	2.3%	2.6%	0.9%
	NMHC	%	1.9%	2.4%	2.8%	1.8%	2.2%	2.3%	2.6%	0.9%
	CO	%	0.6%	1.4%	1.4%	1.0%	1.3%	1.2%	0.8%	0.4%
	NOx	%	0.3%	0.1%	0.3%	0.2%	0.1%	0.1%	0.4%	0.3%
	PM	%	4.1%	9.5%	9.7%	19.5%	8.8%	12.1%	5.3%	21.1%
	CO2	%	0.1%	0.1%	0.2%	0.2%	0.1%	0.1%	0.2%	0.1%
	Work	%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%

TABLE 8. JOHN DEERE 6.8 L BASELINE TAILPIPE EMISSION RESULTS

			NRTC							
			Cold	Hot 1	Hot 2	Hot 3	Composite	Hot-Avg	LLAC	RMC
Average	THC	g/kW-hr	0.005	0.004	0.005	0.005	0.004	0.004	0.005	0.005
	NMHC	g/kW-hr	0.005	0.004	0.004	0.005	0.004	0.004	0.005	0.005
	CO	g/kW-hr	0.245	0.061	0.060	0.062	0.070	0.061	0.000	0.013
	NOx	g/kW-hr	0.387	0.083	0.076	0.076	0.098	0.078	1.826	0.079
	PM	g/kW-hr	0.0014	0.0003	0.0005	0.0005	0.0004	0.0004	0.0003	0.0003
	CO2	g/kW-hr	760.9	747.4	746.8	746.7	748.0	747.0	835.8	696.8
	Work	kW-hr	23.88	23.79	23.77	23.76	23.8	23.77	34.60	51.69
	N2O	kW-hr	0.065	0.069	0.069	0.069	0.069	0.069	0.100	0.053
	PN	#/kW-hr	3.7E+12	5.0E+10	4.9E+10	4.8E+10	4.1E+11	4.9E+10	2.9E+10	1.1E+11
Stdev	THC	g/kW-hr	0.0009	0.0007	0.0007	0.0007	0.0007	0.0007	0.0022	0.0011
	NMHC	g/kW-hr	0.0008	0.0007	0.0007	0.0007	0.0006	0.0007	0.0022	0.0011
	CO	g/kW-hr	0.0124	0.0078	0.0171	0.0155	0.0069	0.0133	0.0000	0.0039
	NOx	g/kW-hr	0.0082	0.0020	0.0022	0.0025	0.0017	0.0014	0.0895	0.0129
	PM	g/kW-hr	0.0009	0.0002	0.0003	0.0003	0.0002	0.0003	0.0003	0.0001
	CO2	g/kW-hr	2.98	3.26	3.74	3.43	3.25	3.47	2.22	0.56
	Work	kW-hr	0.003	0.008	0.004	0.009	0.008	0.007	0.029	0.01
	N2O	kW-hr	0.0018	0.0030	0.0024	0.0028	0.0029	0.0027	0.0040	0.0016
	PN	#/kW-hr	8.9E+11	1.3E+09	2.1E+09	4.4E+09	9.0E+10	2.4E+09	9.0E+08	4.8E+10
COV	THC	%	17%	20%	16%	15%	17%	16%	47%	24%
	NMHC	%	17%	20%	16%	15%	17%	16%	47%	24%
	CO	%	5%	13%	29%	25%	10%	22%	0%	30%
	NOx	%	2.1%	2.4%	2.9%	3.3%	1.8%	1.7%	4.9%	16.2%
	PM	%	68.0%	62.4%	69.3%	47.2%	58.1%	57.9%	85.4%	34.6%
	CO2	%	0.4%	0.4%	0.5%	0.5%	0.4%	0.5%	0.3%	0.1%
	Work	%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%
	N2O	%	2.8%	4.3%	3.4%	4.1%	4.3%	3.9%	4.0%	3.1%
	PN	%	24.0%	2.7%	4.2%	9.1%	21.7%	4.9%	3.1%	45.3%

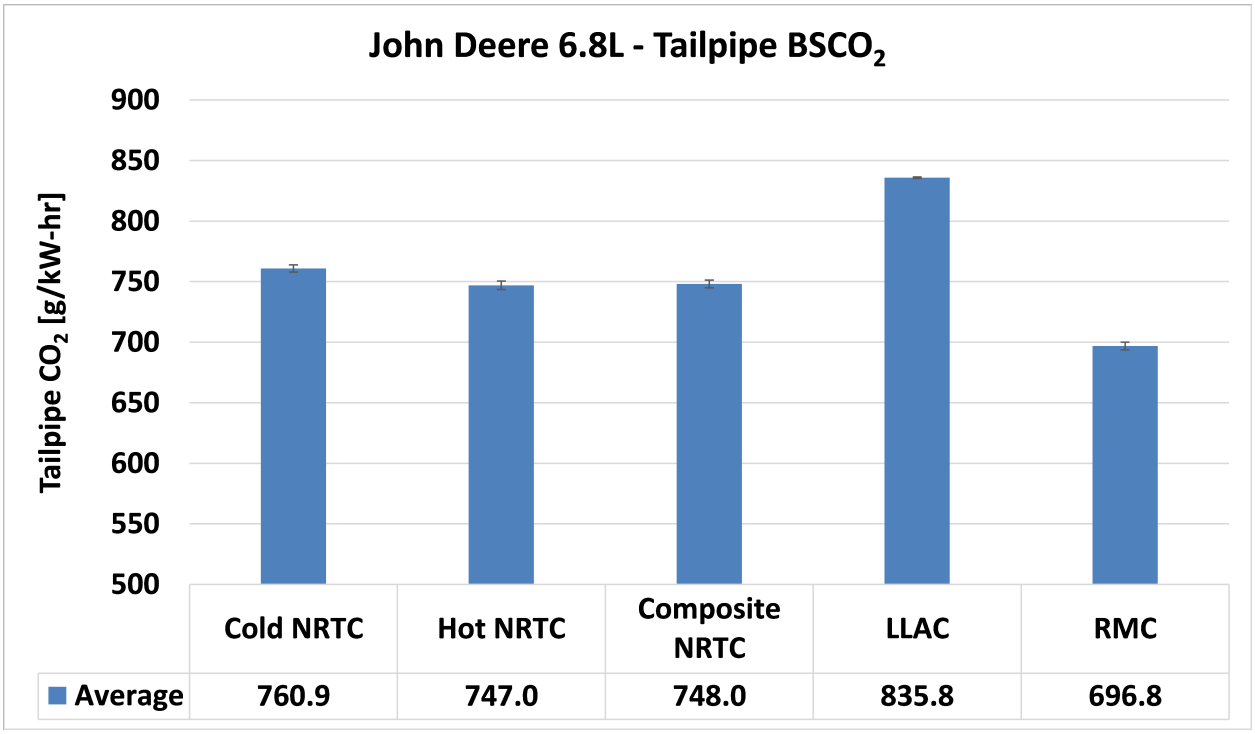
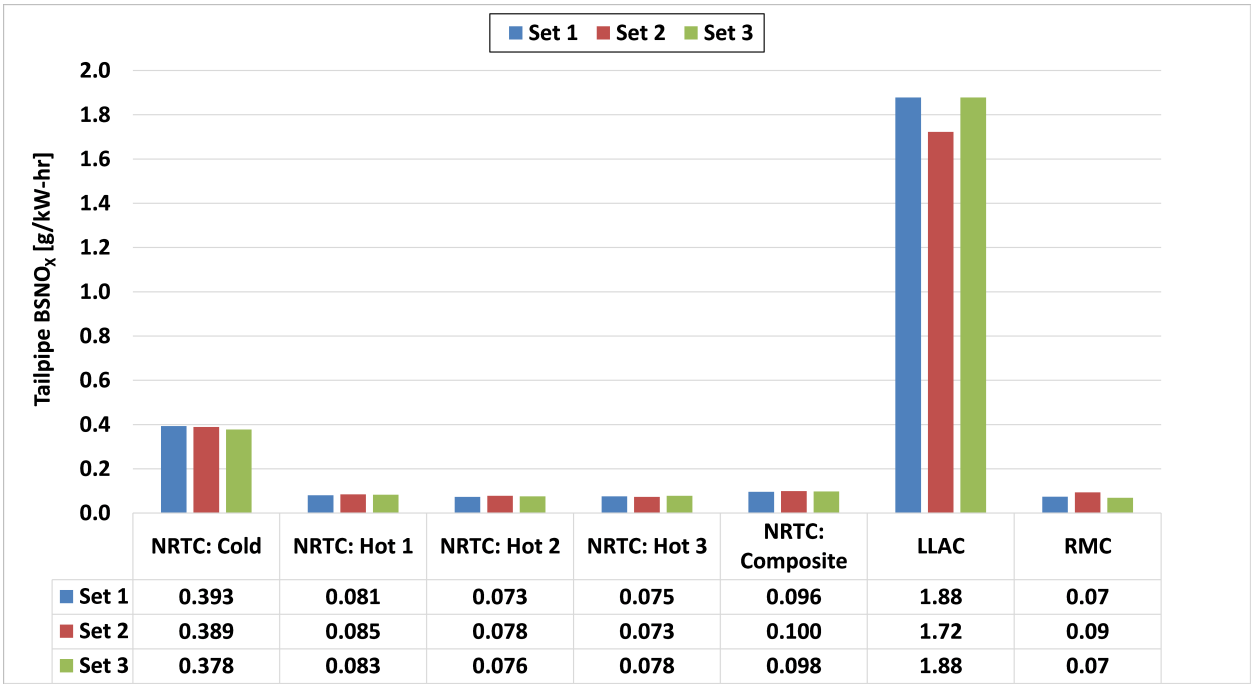


FIGURE 24. JOHN DEERE 6.8 L TAILPIPE CO_2 EMISSIONS

Figure 25 shows the brake specific tailpipe NO_X results from the individual replicates and cycles. The NRTC composite results revealed that the de-greened engine and aftertreatment system produced NO_X emissions well below the Tier 4 final NO_X standard of 0.4 g/kW-hr. The RMC also exhibited low NO_X emissions with an averages of 0.076 g/kW-hr. The LLAC results, however, resulted in tailpipe NO_X that was 4.5X higher than the Tier 4 final NO_X standard. This was expected given that the application's aftertreatment controller calibration was likely configured to comply with the certification cycle testing. In previous work funded by CARB, on-road applications that met the 2010 federal emissions requirements were tested utilizing the LLC. The results revealed aftertreatment system and thermal management issues, which needed to be addressed to meet lower tailpipe NO_X standard targets. This includes sustained low load operation which decreases exhaust temperatures, and maintaining system readiness at low loads to control emissions when the engine resumes higher load operations. Similarly, the LLAC has highlighted areas that will require improvement to meet future regulatory standards the include lower load operations. Additional details will be discussed in subsequent paragraphs.



	NRTC: Cold	NRTC: Hot 1	NRTC: Hot 2	NRTC: Hot 3	NRTC: Composite	LLAC	RMC
Set 1	0.393	0.081	0.073	0.075	0.096	1.88	0.07
Set 2	0.389	0.085	0.078	0.073	0.100	1.72	0.09
Set 3	0.378	0.083	0.076	0.078	0.098	1.88	0.07

FIGURE 25. JOHN DEERE 6.8 L BASELINE TAILPIPE NO_X EMISSIONS

Figure 26 considers the continuous data for a cold start NRTC cycle. Prior to testing this cycle, two (2) hot start preparatory NRTC cycles were executed and followed by an overnight soak period. Since the testing procedures complied with 40 CFR Part 1065, the AT system temperatures remained within 20°C to 30°C. The data highlights low NO_X conversion performance occurring for the first 180 seconds, and this is fairly typical for a modern off-road engine on the cold NRTC. This performance is caused by the low exhaust and catalyst temperatures, which haven't reached the necessary conditions for catalyst light-off. Following 180 seconds, the NO_X conversion performance began to improve significantly with tailpipe NO_X emissions suddenly decreasing. As the AT system temperatures increased, the tailpipe NO_X emissions became very low and eventually achieved NO_X conversion performance of 98% or greater. This performance was observed after 400 seconds into the cold start NRTC. Overall, the NRTC NO_X conversion was reported at 88% in the replicate example shown below.

The next test was a hot start NRTC, which was followed by a 20-minute soak period after the conclusion of the cold start cycle. Figure 27 reflects the continuous data from the hot start NRTC cycle. The AT temperatures are shown to be low at that start of the cycle and contribute to the tailpipe NO_X emissions in the first 150 seconds. Additionally, the tailpipe NO_X mass rate peak was caused by a momentary aftertreatment temperature decrease, which reduced NO_X conversion. Other than the start, NO_X reduction performance remained at full conversion for the rest of the cycle.

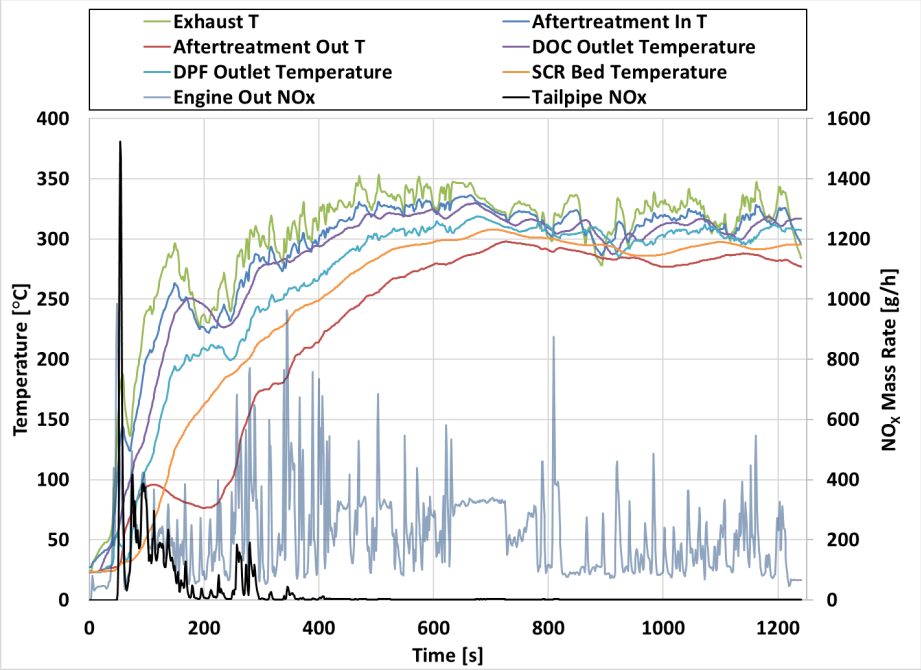


FIGURE 26. JOHN DEERE 6.8 L COLD START NRTC TEMPERATURE AND NO_X PROFILES

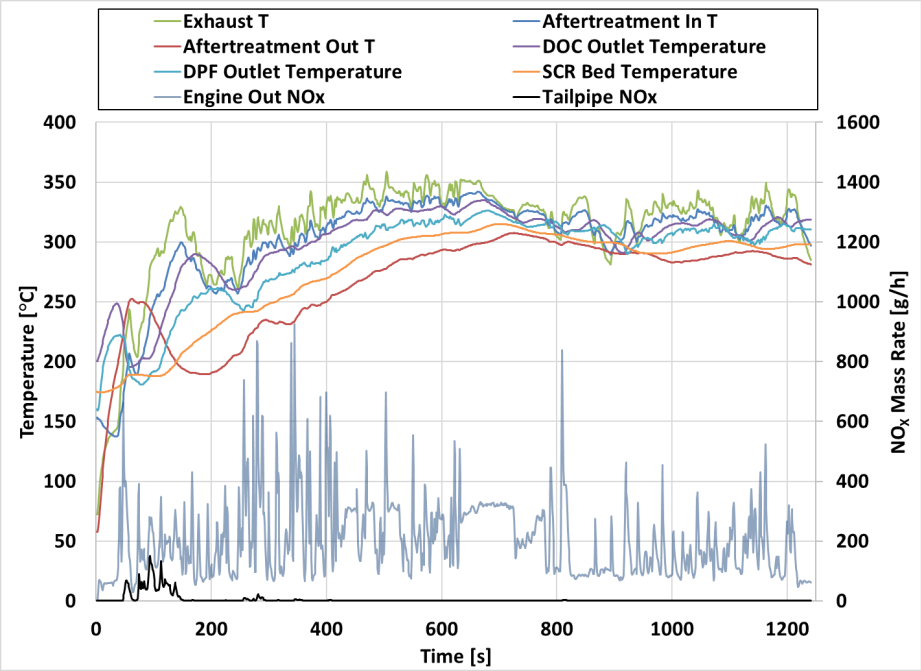


FIGURE 27. JOHN DEERE 6.8 L HOT START NRTC TEMPERATURE AND NO_X PROFILES

After the third hot start NRTC, the LLAC was evaluated with an accessory load. The minimum accessory load for this cycle was configured for 5% with the exception of the motoring segments. Similar to the conventional NRTC cycle execution procedures, the LLAC followed a

20-minute soak period before the test was initiated. With an average duty cycle of 15% the cycle was expected to provide challenges to the baseline hardware and calibration strategies.

Figure 28 considers the continuous NO_X mass rate and temperature data from the LLAC cycle. The temperatures are observed to be operating near the SCR's low temperature limit, or light-off temperature. This temperature behavior was observed at various points within the cycle. Regions where high tailpipe NO_X is observed coincide with an SCR bed temperature at or below 225 °C. When the SCR bed state approached this critical temperature, NO_X control was gradually lost until the AT system returned to an "in-service" state. For example, the cycle featured long idle segments after 3000 seconds and temperatures were observed to decrease over these idle periods. As the temperatures decrease, the SCR catalyst is observed to completely lose its ability to reduce NO_X since the inlet and outlet NO_X mass rates were the same. The engine then entered a momentary load condition where the aftertreatment temperatures increased and the SCR catalyst achieved light off. The low exhaust temperatures resulted in the cycle NO_X conversion of 67%.

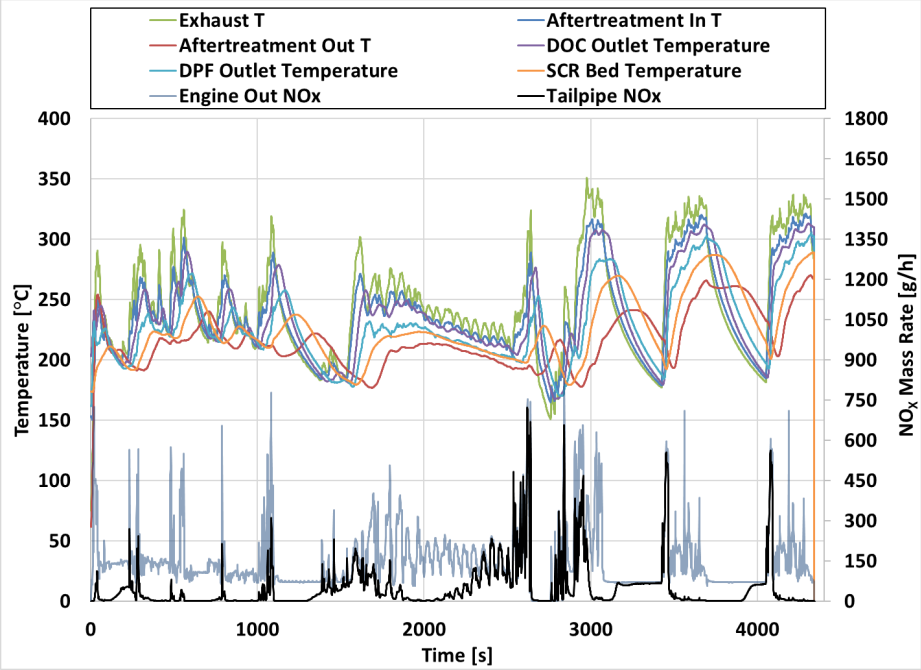


FIGURE 28. JOHN DEERE 6.8 L LLAC TEMPERATURE AND NO_X PROFILES

The baseline RMC cycle is shown in Figure 29. The RMC cycle was observed to have high NO_X conversion performance throughout the cycle with the exception of the first 250 seconds. Specifically, the transition from idle to the first mode is challenging due to the sudden increase in engine out NO_X and because it takes time for temperature to propagate throughout the AT system. Beyond that, the system is shown to have high NO_X reduction for an overall result of 97.6% NO_X conversion.

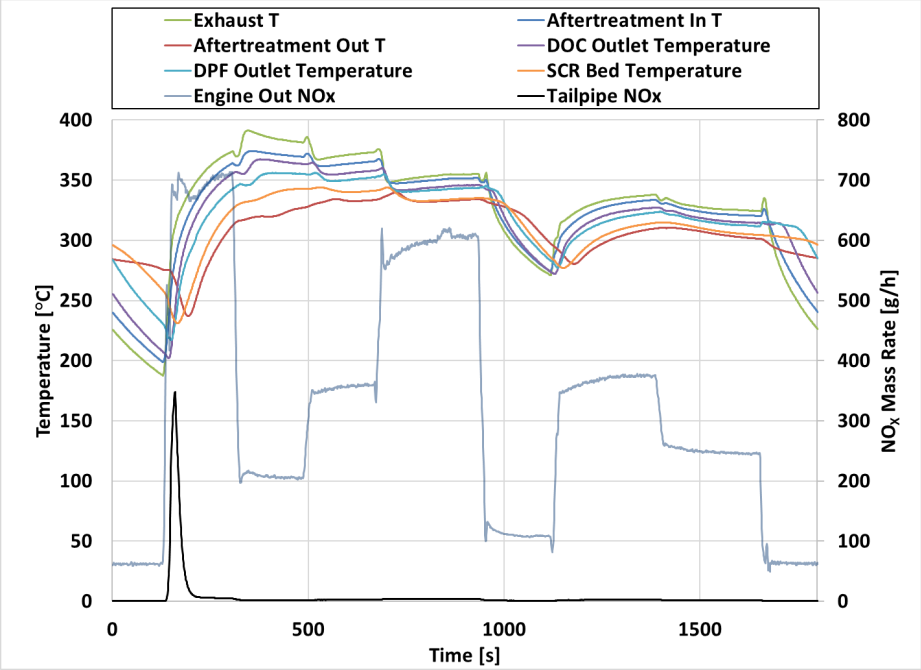


FIGURE 29. JOHN DEERE 6.8 L RMC TEMPERATURE AND NO_X PROFILES

Figure 30, also revealed that the engine and AT system were capable of meeting the Tier 4 final emissions standard of 0.02 g/kW-hr. As expected, the highest amount of PM emissions occurred during the cold start cycle where results were up to 4 times higher compared to the other evaluated cycles. Still, the inclusion of a DPF in the AT system enabled the cold start NRTC result to be lower than the standard. Average results for the remainder of the cycles remained below 0.5 mg/kW-hr.

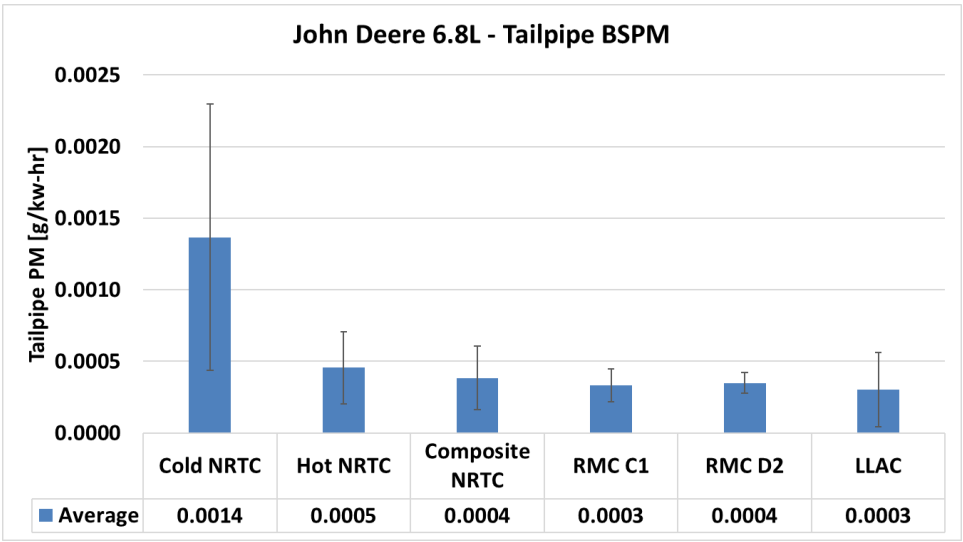


FIGURE 30. JOHN DEERE 6.8 L AVERAGE BSPM TAILPIPE RESULTS

Tailpipe N_2O emissions for the baseline 6.8L engine are given below in Figure 31. Although N_2O is not currently regulated for off-road engines, it is still measured at reported. Generally the base engine was at a level of 0.07 g/kW-hr on the NRTC, and 0.05 g/kW-hr on the RMC. The LLAC was higher at 0.1 g/kW-hr given the lower cycle temperatures, but it should be noted that this cycle did not have very good NO_X control as shown above.

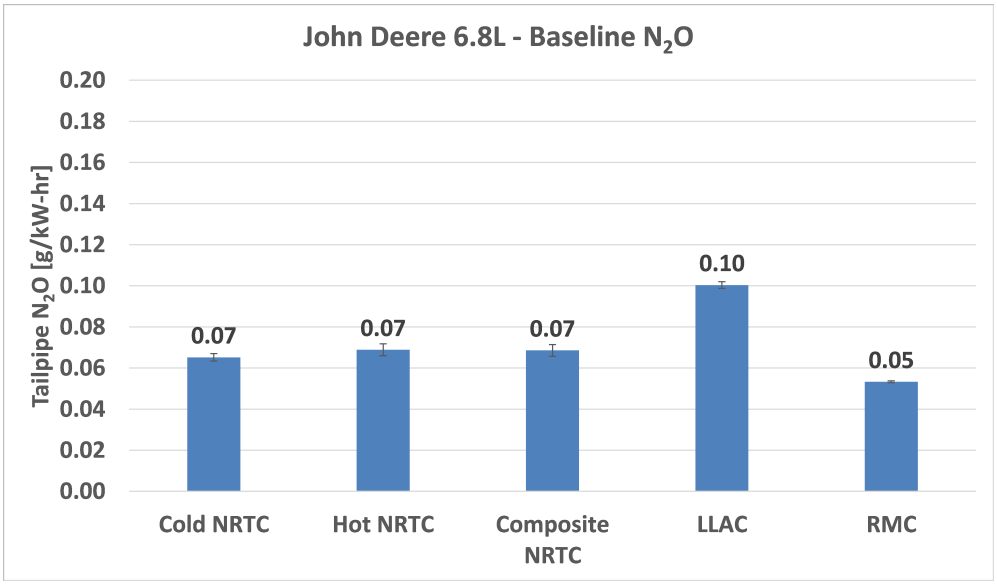


FIGURE 31. JOHN DEERE 6.8L AVERAGE BSN_2O TAILPIPE RESULTS

3.2 Modified Base Engine Calibration Updates

This section describes the development of the modified engine calibration to be used when SCR temperatures are too low to allow high NO_X conversion efficiency. The base AT system and Deere's proprietary ECM access software were used for developing the modified calibration. In addition, combustion quality was monitored with cylinder pressure measurement in each cylinder.

3.2.1. Review of Cold-start NRTC with Base Engine Calibration

From the baseline test results, it is clear that significant tailpipe NO_X reductions are required on all test cycles in order to meet the program targets. While the advanced AT system was expected to provide the majority of the NO_X reduction, no catalytic NO_X control is possible at the beginning of a cold-start NRTC since the AT system starts from room temperature. In addition, reduced SCR NO_X conversion efficiency can be observed during hot-starts if prolonged low load operation causes the SCR temperature to decrease significantly. To gain some insight into the base engine calibration and the potential modifications that would be needed, engine speed, torque, and engine control mode from the first 400 seconds of a cold-start NRTC are shown in Figure 32.

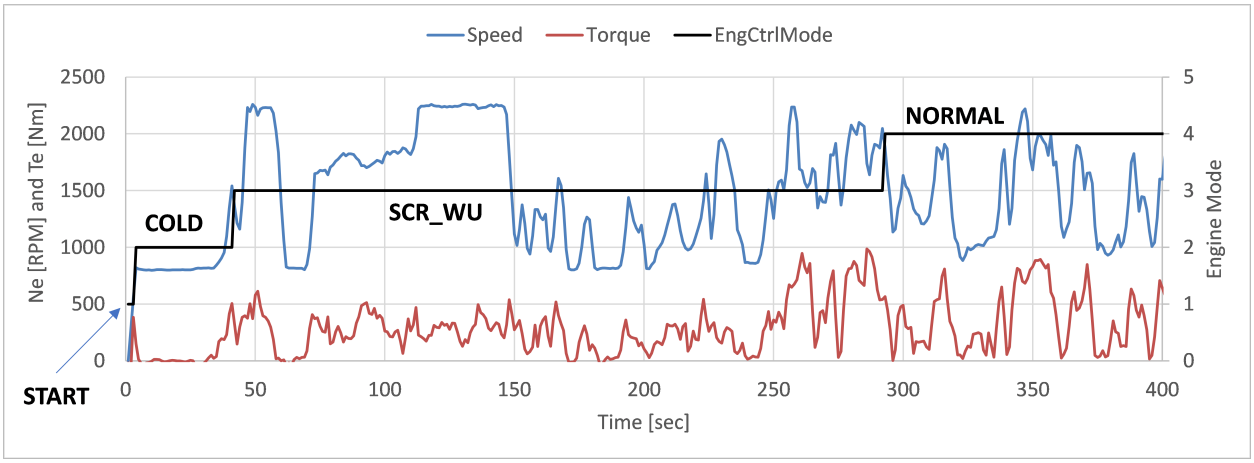


FIGURE 32. COLD-START NRTC CHARACTERISTICS FOR BASELINE ENGINE CALIBRATION: ENGINE SPEED, TORQUE AND ENGINE MODE

Four distinct engine control modes can be observed with the base engine calibration. A "start" mode is used for just a few seconds for engine starting before changing to a "cold" mode which lasts for about 40 seconds. An SCR warm-up mode is then used for about 4 minutes until switching to the final "normal" mode. The corresponding turbine-out and SCR temperature traces along with cumulative engine-out and tailpipe NO_X emissions are shown in Figure 33.

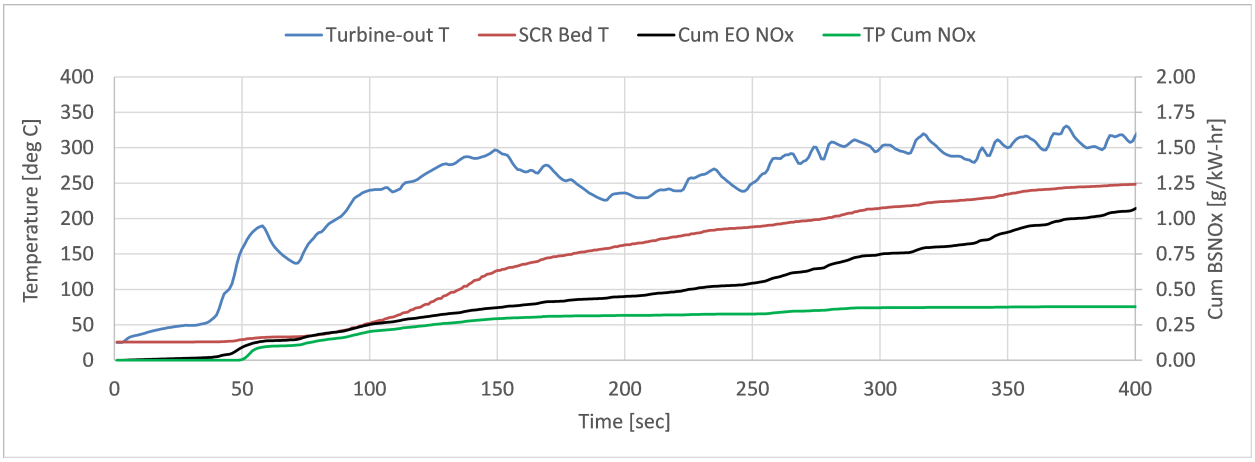


FIGURE 33. COLD-START NRTC CHARACTERISTICS FOR BASELINE ENGINE CALIBRATION: EXHAUST TEMPERATURES AND CUMULATIVE NO_X

The switch to the normal mode corresponds roughly to when an SCR bed temperature of 200°C is reached after which the cumulative tailpipe emissions level off. A typical cold NRTC $BSNO_X$ result was around 0.4 g/kW-hr so it is clear that the majority of the tailpipe NO_X emissions are emitted early in the cycle. Since the NRTC composite is a weighted sum of both the cold and hot-start results, any improvement in cold-start NO_X would ease the required hot-start reduction. Therefore, it was of interest to examine the potential of a modified engine calibration when more aggressive thermal management and reduced engine-out NO_X were needed for cold-start and for the sustained low load operation in the LLAC.

3.2.2. Steady-state Test Points for Calibration Development

As a starting point, the performance of the available base engine operation modes was assessed over several steady-state speed and load conditions. The test points used for initial calibration development are listed in Table 9 and are plotted on a speed and load scatter plot in Figure 34 which includes data from the first 400 seconds of the NRTC and the complete LLAC.

TABLE 9. ENGINE SPEEDS AND LOADS FOR SELECTED STEADY-STATE TEST POINTS FOR MODIFIED CALIBRATION DEVELOPMENT

Test Point	Engine Speed	Load	
-	[rpm]	BMEP [bar]	Torque [Nm]
1	800	0	0
2	1200	2.8	150
3	1200	5.5	300
4	1200	11.1	600
5	1600	2.8	150
6	1600	5.5	300
7	1600	11.1	600
8	2200	2.8	150
9	2200	5.5	300
10	2200	11.1	600

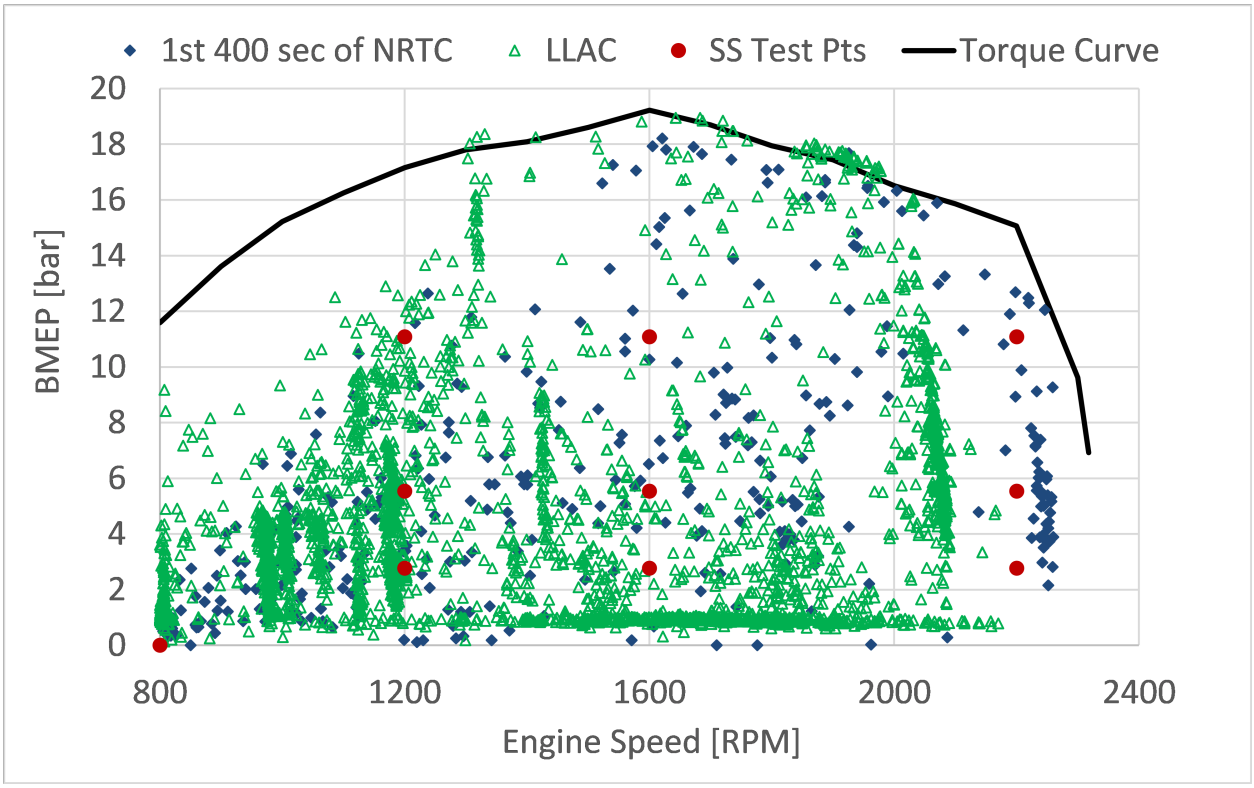


FIGURE 34. RELATION OF SELECTED CALIBRATION TEST POINTS TO FIRST 400 SECONDS OF NRTC AND COMPLETE LLAC

3.2.3. Steady-state Testing for Modified Cold Calibration Development

Since the base engine calibration used several different engine modes during the cold-start NRTC, the performance of these modes was documented at the selected test points. Next, the calibration space was explored to see if increased exhaust gas temperature and reduced engine-out NO_X could be achieved for a more aggressive thermal management mode. The baseline results along with the new thermal management calibrations (TM-1 and TM-2) are shown in the following sections. The different calibration modes are referred to as:

1. Cold = baseline calibration used for a short time at the beginning of a cold-start
2. SCR_WU = baseline calibration SCR warm-up mode used when SCR temperature is low
3. Normal = baseline calibration used when both coolant and SCR are warm
4. ATM = baseline calibration used during DPF regeneration
5. TM1 = Modified calibration for aggressive thermal management and reduced engine-out NO_X intended for early portion of cold-start and when SCR temperature is too low.
6. TM2 = Less aggressive thermal management mode intended for when SCR temperature is less than optimal but not too low such that conversion efficiency is significantly compromised

For brevity, only results obtained at idle and a few loaded test points are shown in the following sections. It should also be noted that all test results presented were obtained with hot coolant (90°C).

3.2.3.1 - Test Point 1: Idle

Test results obtained at idle (800 rpm, 0 Nm) are shown in Figure 35. Since temperature is only one aspect of heating a cold catalyst, all test results are plotted against exhaust enthalpy which considers both temperature and exhaust flow rate and is an important factor when heating a cold catalyst. The engine-out NO_X and fuel flow rates were normalized with respect to the base normal mode. As shown, the base ATM calibration used during DPF regeneration had the highest turbine-out temperature without sacrificing enthalpy and had a significant engine-out NO_X reduction, but a 60% increase in fuel consumption. However, it was expected that higher fuel consumption during the more aggressive thermal management modes would be incurred. Therefore, the calibration settings for the base ATM mode at idle were selected for the modified thermal management mode TM1. When moderate thermal management is needed, the base SCR_WU mode provided slightly higher exhaust temperature with only a 15% fuel consumption increase so these settings were selected for TM2.

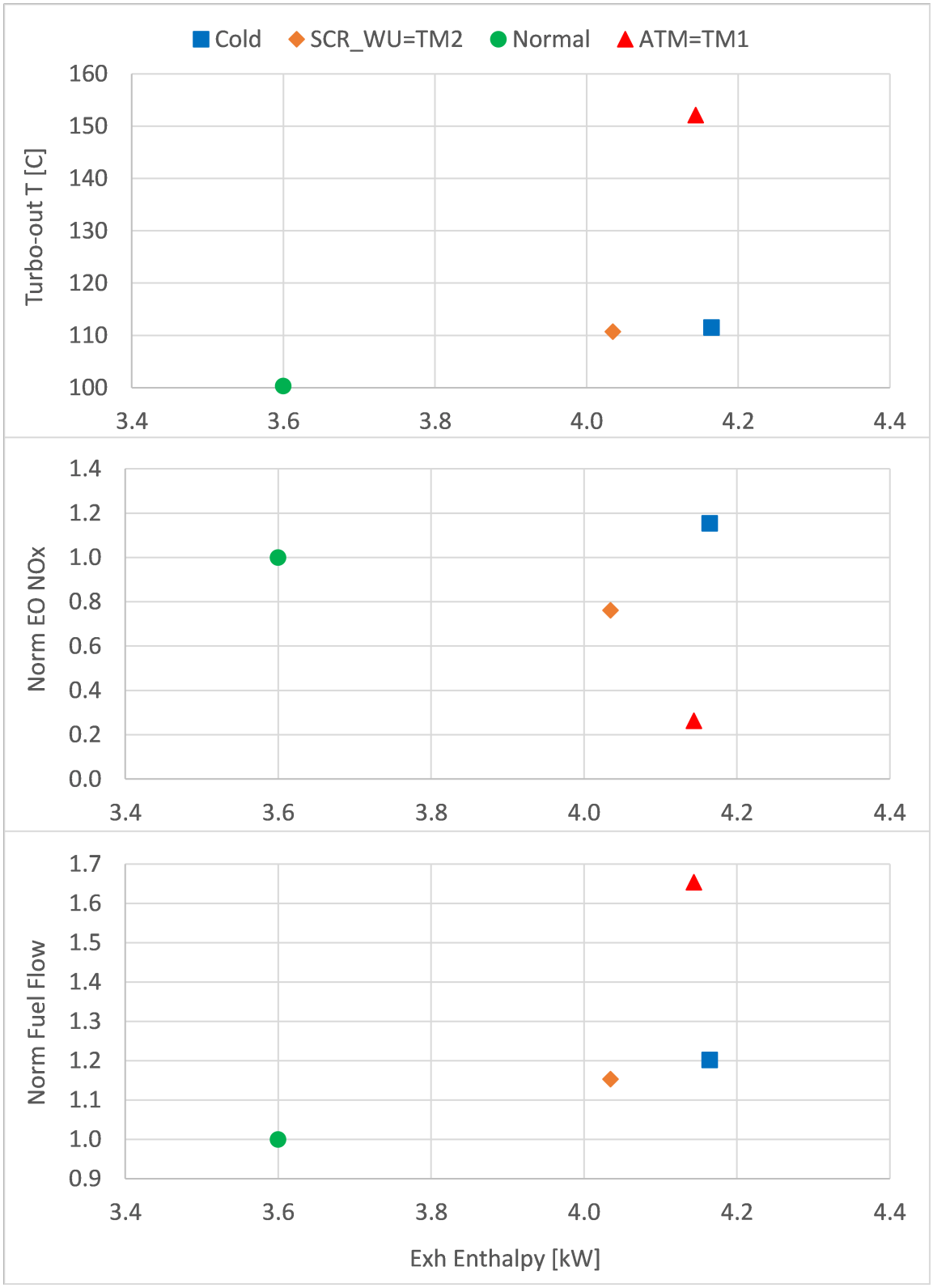


FIGURE 35. IDLE TEST POINT RESULTS FOR BASELINE AND THERMAL MANAGEMENT CALIBRATIONS TM1 AND TM2

In addition to the calibrations for low SCR temperature conditions, two potential stay hot strategies for reducing exhaust mass flow rate (and hence SCR cooling) at idle were evaluated. These strategies included intake throttling and EGR cooler bypass and were evaluated with the normal engine calibration. Turbine-out temperature, normalized engine-out NO_X and fuel flow rate plotted against exhaust flow rate are shown in Figure 36.

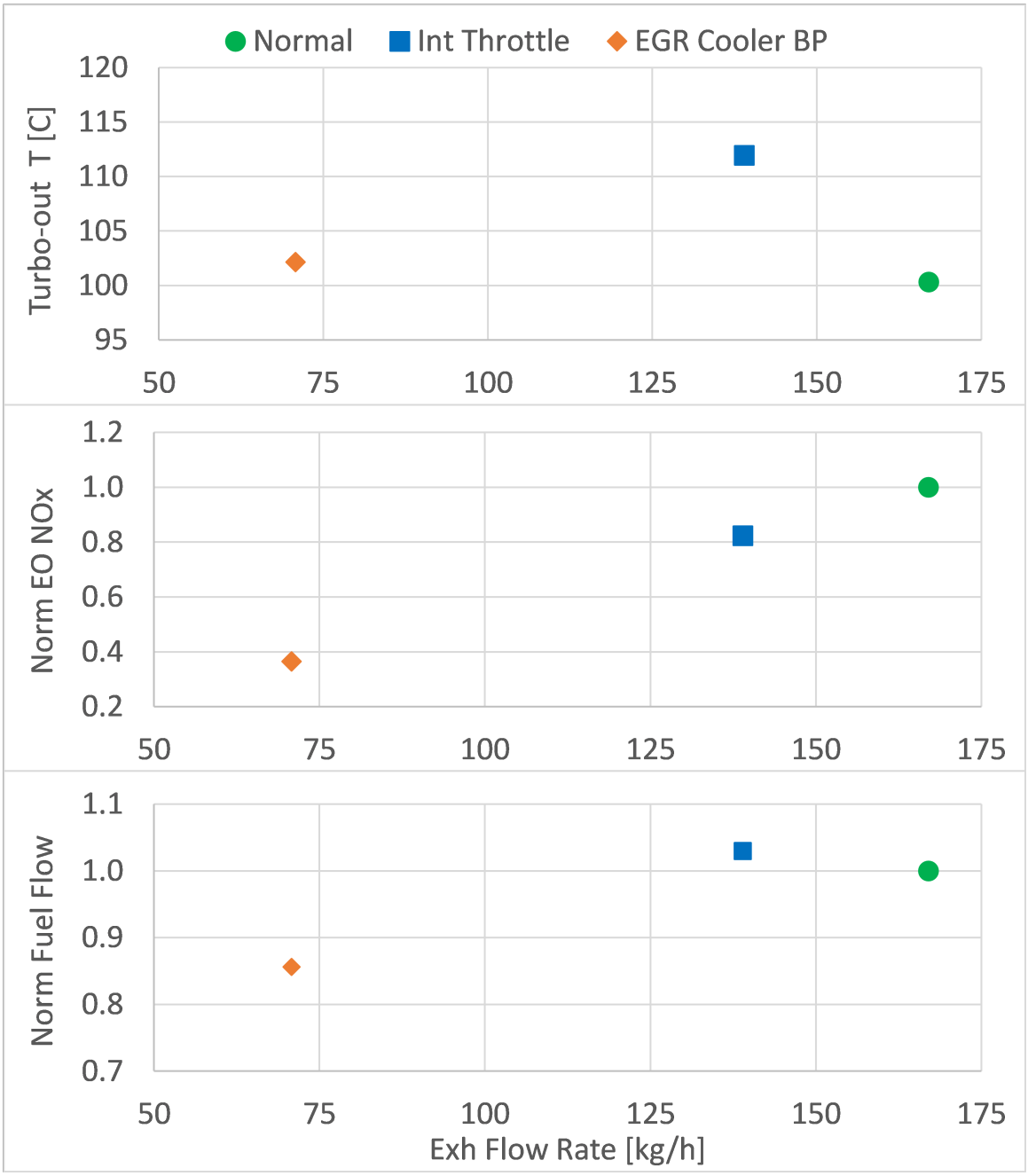


FIGURE 36. IDLE RESULTS FOR NORMAL CALIBRATION WITH INTAKE THROTTLING AND EGR COOLER BYPASS FOR POTENTIAL STAY HOT OPERATION

Intake throttling gave a moderate reduction in exhaust flow rate and a slight increase in turbine-out temperature at the expense of a fuel flow increase. EGR cooler bypass provided the most significant exhaust flow rate reduction of nearly 50% with a reduction in fuel consumption. Although not the main parameter of interest for stay warm, it is worth noting that the EGR cooler bypass also reduced the engine-out NO_X by 60%.

3.2.3.2 - Test Points 2, 5 and 8: 150 Nm at 1200, 1600 and 2200 rpm

Steady-state turbine-out temperature, exhaust enthalpy, normalized engine-out NO_X and soot mass obtained at 150 Nm and the three engine speeds: 1200, 1600, and 2200 rpm, are shown in Figure 37, Figure 38, and Figure 39, to illustrate the typical trade-offs between the available base engine control modes and the modified thermal management modes. The NO_X and soot mass flow rates were normalized to the base normal mode. The soot mass flow rates were calculated using estimated soot concentration from the smoke meter and exhaust flow rate. In terms of temperature, the base cold mode had the lowest temperature, but the second highest exhaust enthalpy behind the ATM mode. However, the high exhaust enthalpy was due to high exhaust flow rate associated with no EGR which resulted in the highest engine-out NO_X. The base ATM mode generally had the highest temperature and enthalpy, but the NO_X was also high due to no EGR. For TM1, a lower engine-out NO_X was required so EGR was added to the ATM calibration while limiting the engine-out smoke to 2.0 filter smoke number (FSN) resulting in the TM1 result shown. The base SCR_WU mode provided a 50 to 100°C exhaust temperature increase over the base normal mode without a significant NO_X increase, so this calibration was selected for TM2. Similar results were obtained at the other engine loads so only the 150 Nm results are shown.

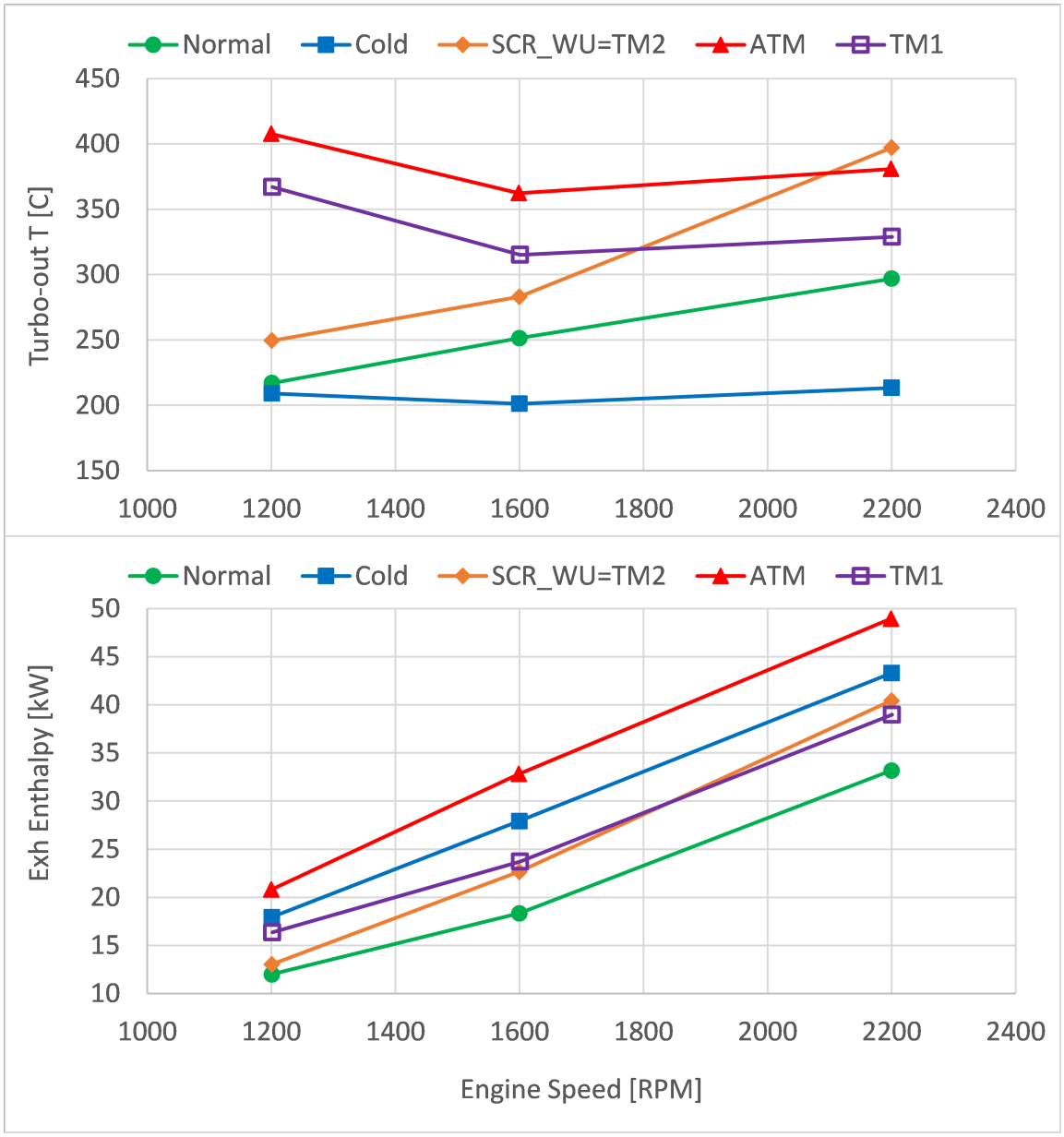


FIGURE 37. TURBINE-OUT TEMPERATURE AND EXHAUST ENTHALPY RESULTS AT 150 NM FOR BASE AND THERMAL MANAGEMENT CALIBRATIONS TM1 AND TM2

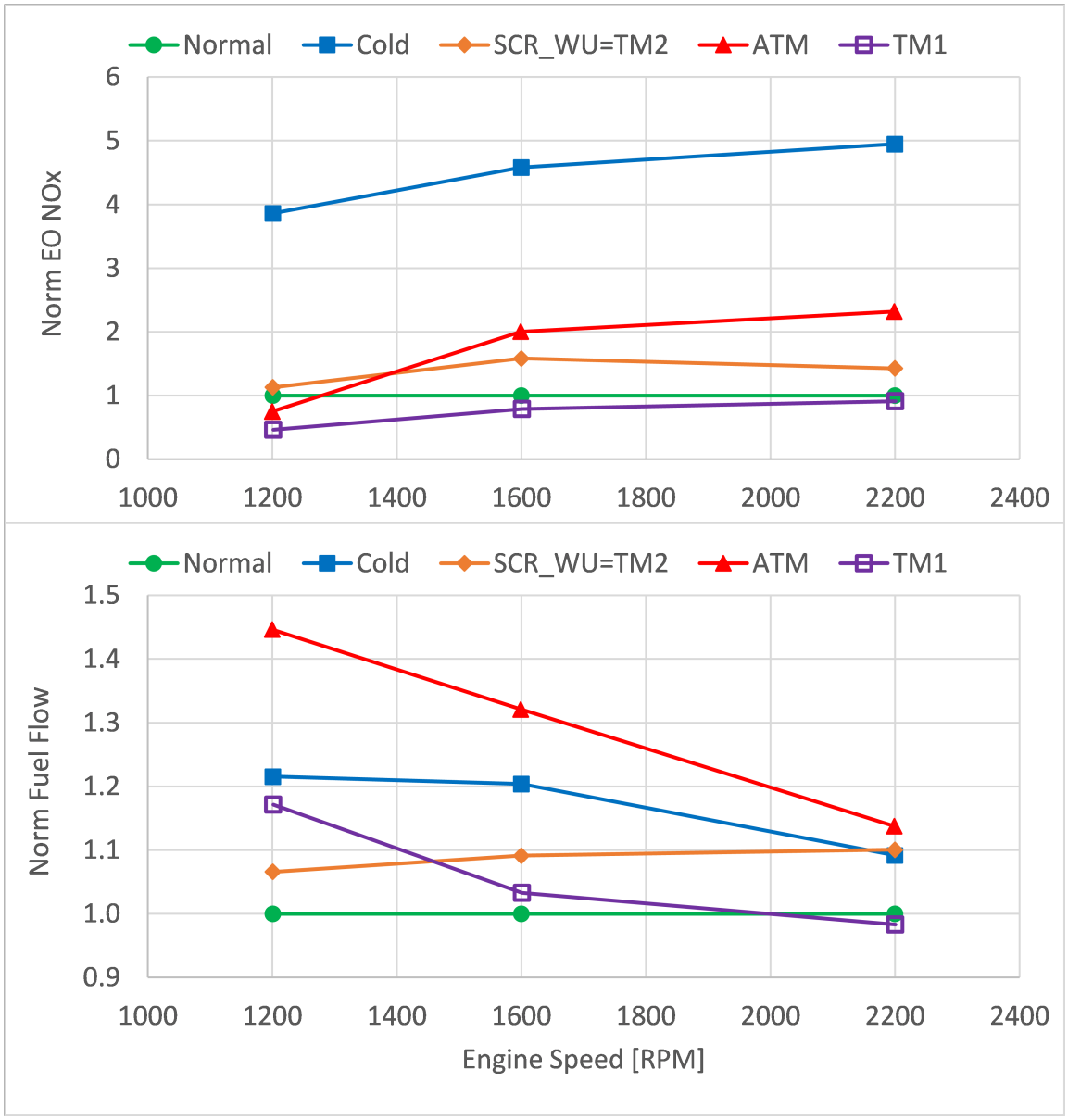


FIGURE 38. NORMALIZED ENGINE-OUT NO_X AND FUEL FLOW RESULTS AT 150 NM FOR BASE AND THERMAL MANAGEMENT CALIBRATIONS TM1 AND TM2

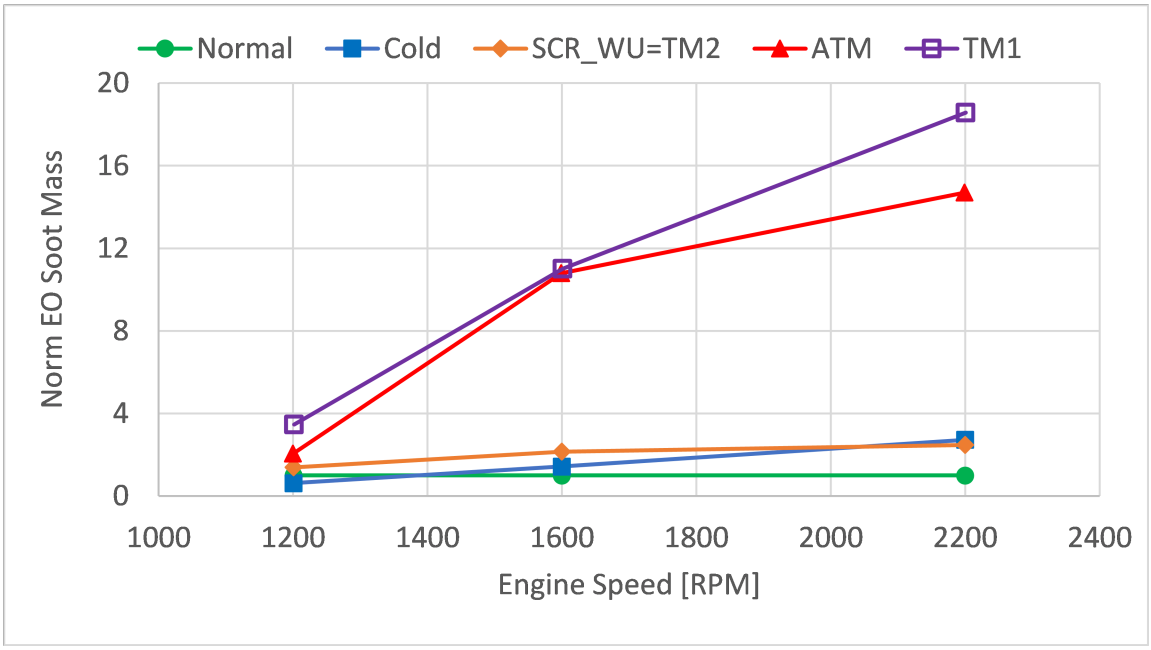


FIGURE 39. ENGINE-OUT SMOKE AT 150 NM FOR BASE AND THERMAL MANAGEMENT CALIBRATIONS TM1 AND TM2

3.2.4. Transient Evaluations with the Modified Engine Calibrations

Based on the steady-state calibration efforts, a modified thermal management calibration (TM1) was developed and implemented in the ECM. A custom engine control mode selector, or state machine, was implemented in the supervisory engine controller as discussed previously which used the stock SCR bed temperature as an input since the base AT system was installed for this task. The calibrations available to the state machine were TM-1, TM-2, and the normal modes. Since the state machine had a slight delay (used engine speed to trigger), the engine still started in the original "start" mode. Results obtained with the modified calibration over the cold NRTC are shown in Figure 40 and Figure 41.

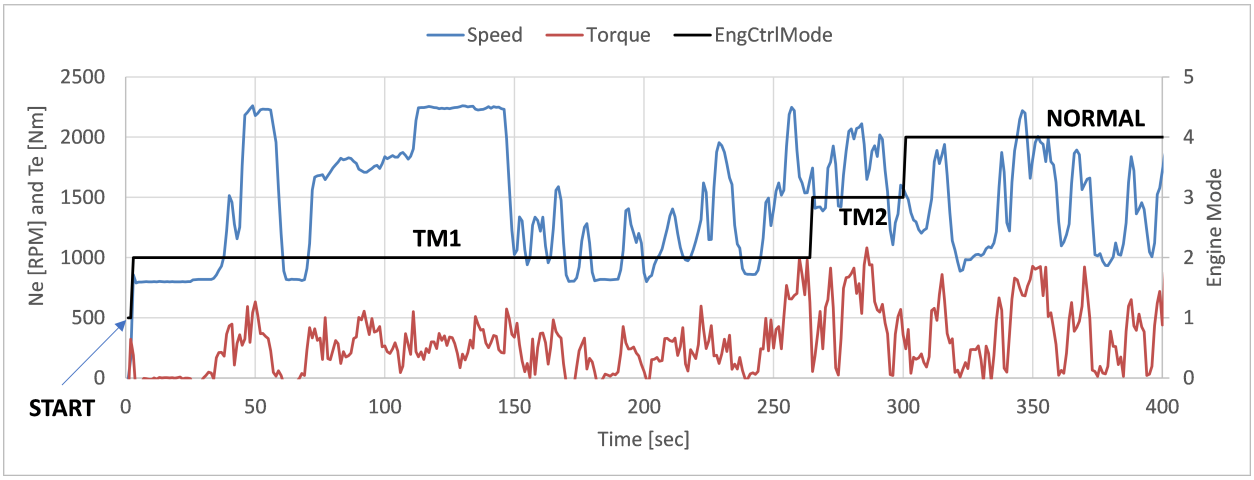


FIGURE 40. COLD-START NRTC RESULTS FOR MODIFIED ENGINE CALIBRATION: ENGINE SPEED, TORQUE AND ENGINE MODE

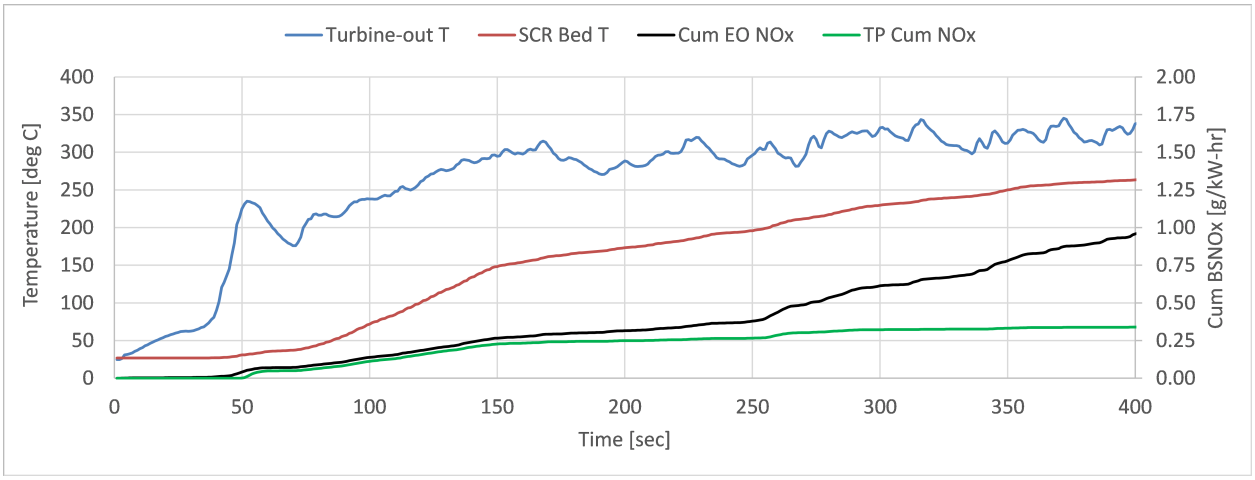


FIGURE 41. COLD-START NRTC RESULTS FOR MODIFIED ENGINE CALIBRATION: EXHAUST TEMPERATURES AND CUMULATIVE NO_X

To better see the impact of the modified calibration TM1, the turbine-out and SCR bed temperature traces for both the baseline and modified calibrations are shown in Figure 42 and the cumulative engine-out and tailpipe NO_X emissions are shown in Figure 43. TM1 provided a turbine-out temperature increase of 50°C except for between 100 and 150 seconds where the base SCR warm-up mode had similar exhaust temperatures. The increased turbine-out temperatures along with similar exhaust enthalpy resulted in a 20 second reduction to reach 200°C SCR bed temperature. At the same time, the modified calibration had significantly lower cumulative NO_X emissions. Some key comparison parameters are listed in Table 10.

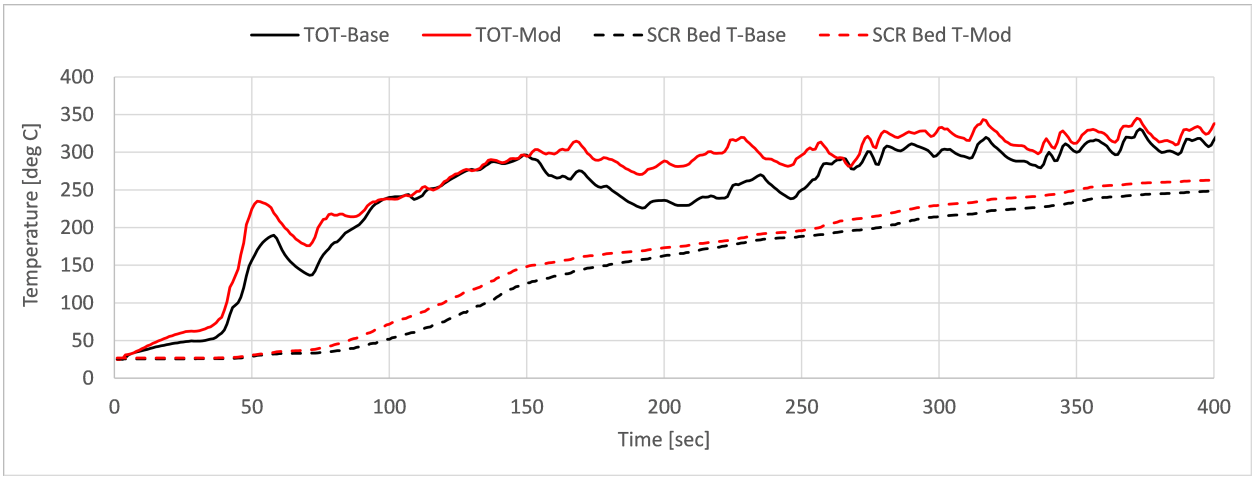


FIGURE 42. TURBINE-OUT AND SCR BED TEMPERATURE COMPARISON BETWEEN BASE AND MODIFIED CALIBRATIONS DURING FIRST 400 SECONDS OF A COLD-START NRTC

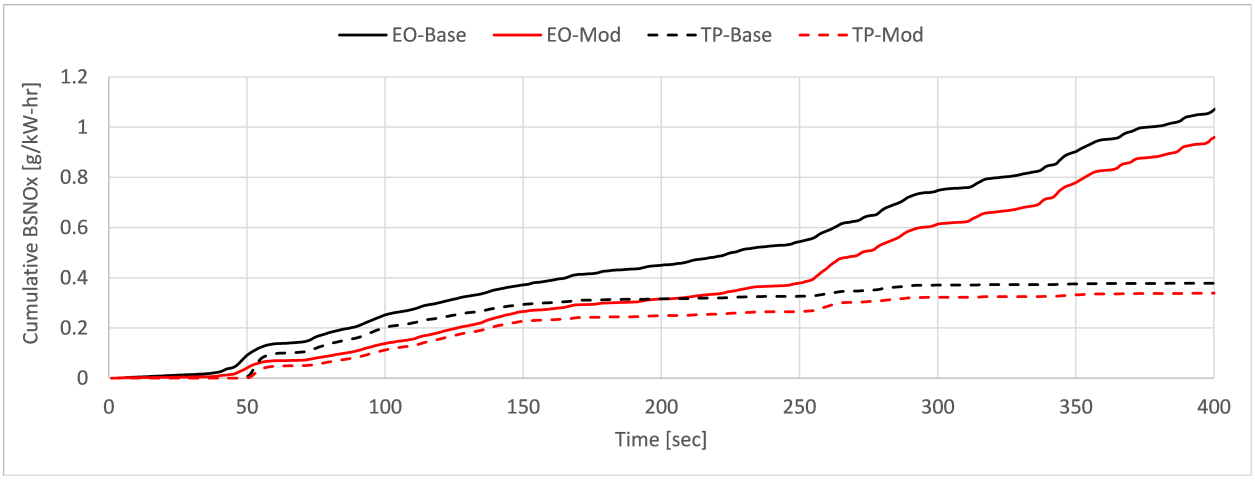


FIGURE 43. CUMULATIVE ENGINE-OUT AND TAILPIPE BSNOX COMPARISON BETWEEN BASE AND MODIFIED CALIBRATIONS DURING FIRST 400 SECONDS OF A COLD-START NRTC

TABLE 10. COLD-START NRTC PERFORMANCE COMPARISON FOR BASE AND MODIFIED CALIBRATIONS WITH BASE AFTERTREATMENT

		Base	Mod
Run #		4333	6402
$t_{200°C}$ (Time to 200°C SCR Bed Temperature)	sec	276	255
Cumulative Engine-out $BSNO_X$ at $t_{200°C}$	g/kW-hr	0.65	0.40
Cumulative Tailpipe $BSNO_X$ at $t_{200°C}$	g/kW-hr	0.35	0.27
Cycle $BSCO_2$	g/kW-hr	758	775
Cycle Tailpipe $BSNO_X$	g/kW-hr	0.39	0.36

As shown in Table 10 and consistent with the steady-state results, the engine measures used to achieve higher exhaust temperature and reduced engine-out NO_X were not fuel neutral with a 2.5% cycle CO_2 increase observed for the two cases presented with the base AT system. The TM1 and TM2 calibrations described in this section were used for both engine hardware packages.

3.3 Package 2 Engine Calibrations

This section describes the development of the modified engine calibrations for Package 2 with reduced GHG emissions. The Package 2 calibration differs from Package 1 by adding CDA hardware which requires its own calibration and control logic along with a more fuel efficient "normal" operating mode calibration with advanced injection timing and higher engine-out NO_X. It was expected that the advanced AT systems would have the capability to handle the higher engine-out NO_X levels and still achieve the program tailpipe NO_X targets.

The base AT system and Deere's proprietary ECM access software were used for developing the Package 2 calibrations. The control software for the CDA hardware was implemented in a supervisory controller with fast communication access with the engine ECM and special provisions to allow individual cylinder fuel control on a cycle-by-cycle basis. In addition, combustion quality was monitored with cylinder pressure measurement in each cylinder.

3.3.1. Revised Normal Mode for Package 2

Although CDA is widely known for improving fuel consumption, the benefits are limited to about 4 bar brake mean effective pressure (BMEP), which was at a torque of 215 Nm on this test engine. Therefore, CDA alone would not be sufficient to achieve the Package 2 GHG reduction target of 5-8.6% due to the frequent high load operations during the NRTC and RMC cycles. Therefore, the base normal calibration was modified to reduce the fuel consumption with advanced injection timing and reduced EGR rate targets. The maximum timing advance at full load was limited by the peak cylinder pressure limit provided by Deere. To illustrate the typical trade-offs between injection timing, CO_2, engine-out NO_X and smoke, experimental results obtained at 300 Nm are shown in Figure 44. The data sets shown correspond to a Base, which in this case is the Package 1 calibration, exploratory tests, and the final Package 2 low GHG calibration. Although not shown, the EGR rate was also a calibration knob and the injection pattern at this load was a double (pilot + main) injection so the pilot timing was moved by the same amount as the main.

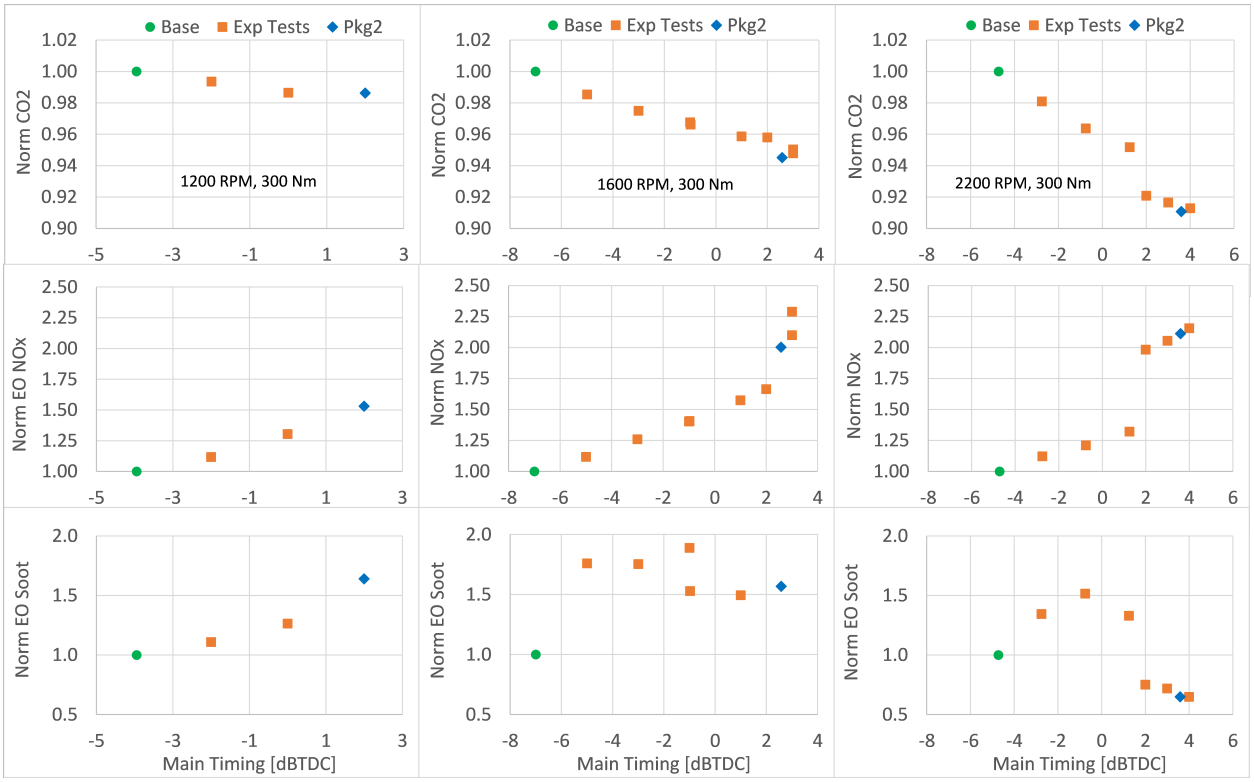


FIGURE 44. PACKAGE 2 CALIBRATION DEVELOPMENT EXAMPLE AT 300 NM

As expected, CO_2 decreased with advanced injection timing, however the reduction amount varied with engine speed with less than 2% at 1200 rpm compared to over 8% at 2200 rpm. The engine-out NO_X increased with advanced timing with a 50 to 100% increase over the baseline for the final Package 2 calibration. Advancing the injection timing generally increased the soot mass with an acceptable 50% increase for the final Package 2 calibration except for 2200 rpm where a reduction in EGR resulted in a lower soot than the baseline, additional CO_2 reduction, and increased NO_X.

3.3.2. CDA Calibrations for Package 2

After installation of the CDA hardware and performing initial control code checks such as CDA solenoid timing, fuel cut, valve deactivation, and valve reactivation, speed ramps under various fixed CDA modes were performed to determine if any CDA modes caused unacceptable torsional vibration due to excitement of the dyno coupling resonant frequency. The engine load was maintained at 0 bar BMEP and the speed was ramped from 750 rpm to 2200 rpm at a rate of 25 rpm/sec. Outputs from a 0.2 crank angle degree resolution shaft encoder were sampled at high frequency with a ROTEC measuring system to generate and analyze the torsional vibration data. Measurements were also acquired from linear vibration accelerometers on the engine mounts and the resulting amplitudes were found to be at acceptable levels at all engine speeds.

The resulting 1st order angular acceleration had the highest response and is shown in Figure 45. Both the 2-cylinder and 4-cylinder firing modes (2cCF and 4cCF) had unacceptable torsional vibration below 1100 rpm. Generally, 500 rad/s^2 is an upper limit. Therefore, the only CDA mode that was available from idle (800 rpm) to 1100 rpm was 3CF.

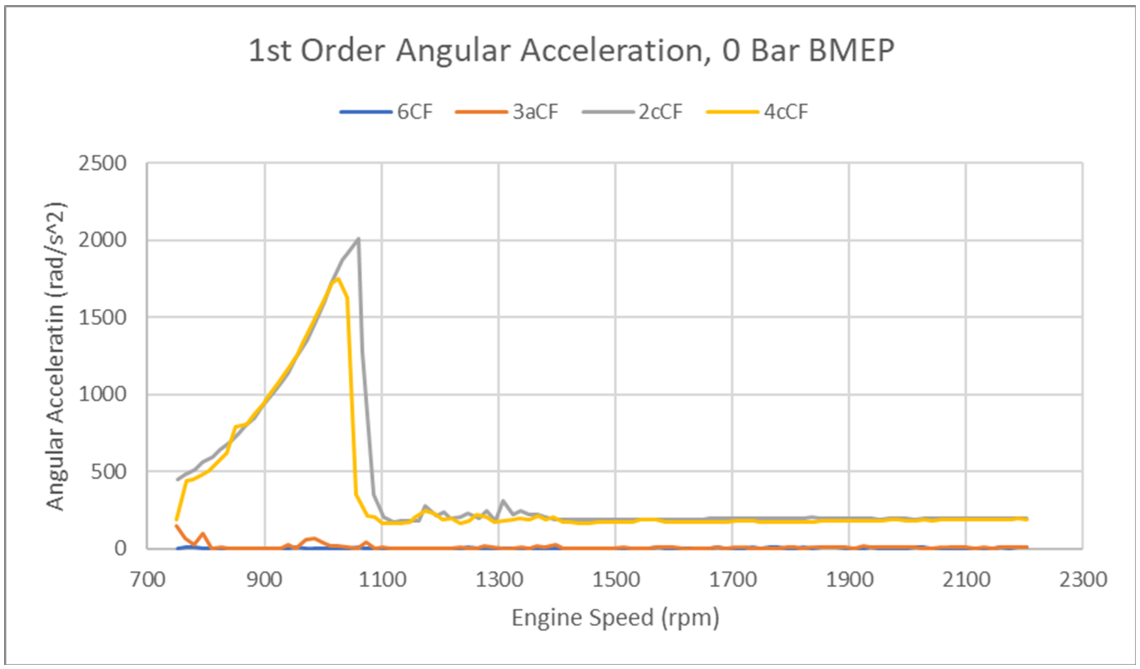


FIGURE 45. FIRST ORDER ANGULAR ACCELERATION MEASURED DURING ENGINE SPEED RAMPS WITH DIFFERENT CDA MODES

3.3.2.1. CDA Recipe (CDA-R) Calibration

To distinguish between the SwRI CDA recipe and Tula's dDSF control implementations, the former is referred to as "CDA-R" while the latter is referred to as "DSF" in this report. Both CDA versions had the constraint of no 2CF or 4CF modes below 1100 rpm, for NVH reasons. For CDA-R mode selection above 1100 rpm, steady-state tests were conducted at several engine loads with all available cylinder combinations at each CDA mode (i.e.. 2CF mode has 3 possible combinations, 3CF has 2 combinations, and 4CF has 3 combinations) using the Package 2 FE calibration (revised fueling and EGR targets). Example test results obtained at 1200 rpm and three load levels are shown in Figure 46 while results obtained at a fixed load of 2 bar BMEP and three engine speeds are shown in Figure 47. The parameters shown include normalized CO_2 (key parameter of interest for Package 2), normalized engine-out NO_X, and normalized engine-out soot mass all plotted against turbine-out temperature. The normalization was with respect to the Package 2 6CF result, so the CDA results represent changes due to CDA. The soot mass was calculated using estimated soot concentration from the smoke meter and exhaust flow rate. It should be noted that the use of soot mass flow rate instead of filter smoke number is a better indicator of smoke change during CDA due to the significant change in exhaust flow rate.

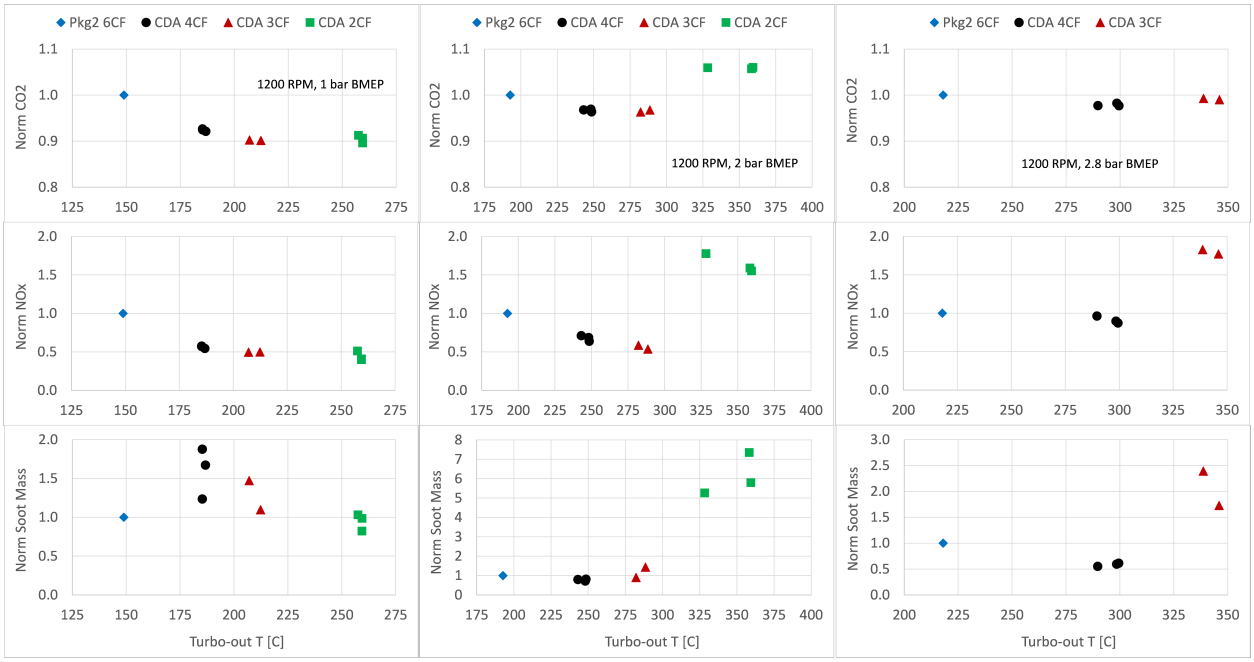


FIGURE 46. CDA MODE COMPARISON AT 1200 RPM AND 1, 2, AND 2.8 BAR BMEP

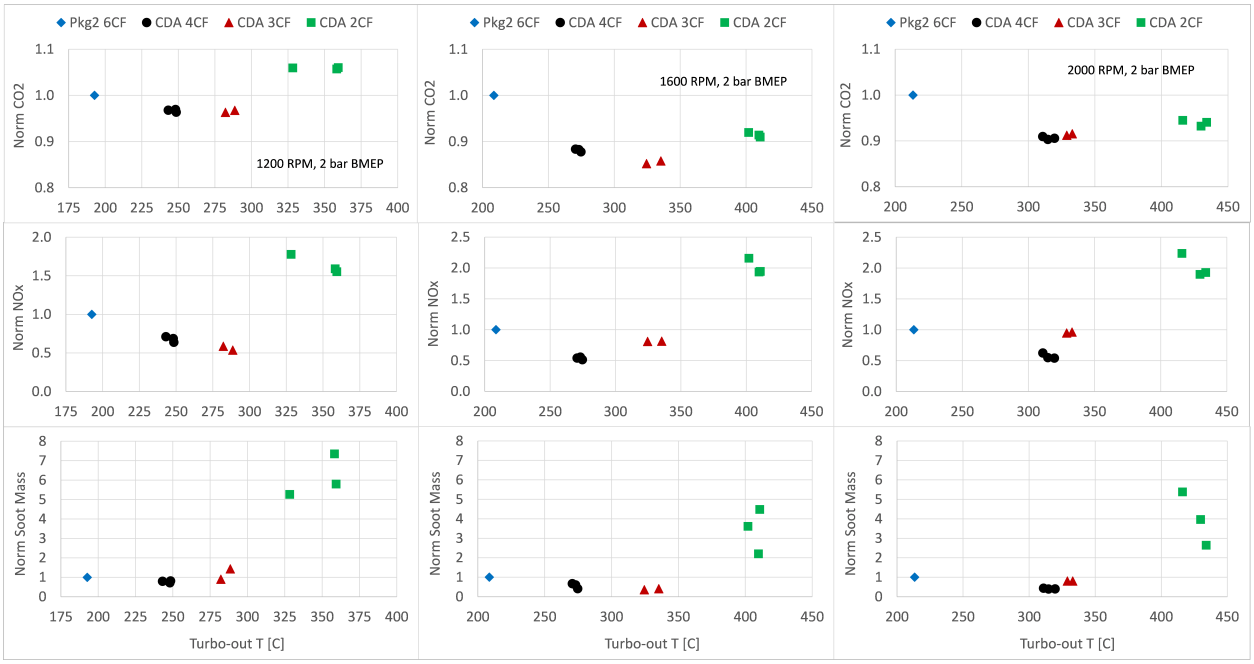


FIGURE 47. CDA MODE COMPARISON AT 2 BAR BMEP AND 1200, 1600, AND 2000 RPM

In general, little variation in the results were observed for a given CDA mode and the various cylinder combinations. For 1200 rpm and 1 bar BMEP, decreasing the number of cylinders fired reduced CO_2 and increased turbine-out temperature. Since the CO_2, NO_X and smoke results were similar for the 2 and 3CF cases, 2CF was chosen due to the higher exhaust temperature which

would be beneficial for keeping the AT system hot. At 2 bar BMEP, 2CF modes had higher CO_2 and smoke indicating that insufficient boost was available. The 3 and 4CF cases had similar results so 3CF mode was selected for the increased exhaust temperature. At 2.8 bar BMEP, the CO_2 reduction by CDA was diminishing with similar CO_2 amounts for 3 and 4CF modes. However, since the 3CF mode had higher smoke, 4CF was chosen. At 2 bar BMEP, the CO_2 reduction amount varied with engine speed with the minimum at 1200 rpm and the maximum at 1600 rpm. For this load, 3CF was selected due to the combination of low CO_2, acceptable NO_X, soot mass and higher temperature than 4CF. This selection method was followed for other engine speeds and loads until a complete CDA-R mode map was determined for the Package 2 FE map as shown in Table 11. For CDA-R, the inputs for CDA mode selection were engine speed and unmodified per cylinder fueling read from the ECM, however an approximate load is given in the table for reference as the actual fuel values are proprietary. A nearest-neighbor type of interpolation, which also provides hysteresis, was used since the table entries were discrete CDA modes.

TABLE 11. CDA-R TABLE FOR PACKAGE 2 FE (MODE 4)

Approx BMEP, bar		0	1	1.5	2	3	3.5	4
	800	3CF	3CF	3CF	3CF	6CF	6CF	6CF
	850	3CF	3CF	3CF	3CF	6CF	6CF	6CF
	900	1CF	3CF	3CF	3CF	6CF	6CF	6CF
	1000	1CF	3CF	3CF	3CF	3CF	6CF	6CF
	1100	1CF	3CF	3CF	3CF	3CF	6CF	6CF
	1200	1CF	2CF	2CF	3CF	4CF	6CF	6CF
Speed, rpm	1300	1CF	2CF	2CF	3CF	4CF	6CF	6CF
	1400	1CF	2CF	3CF	3CF	4CF	6CF	6CF
	1500	1CF	2CF	3CF	3CF	4CF	6CF	6CF
	1600	1CF	2CF	3CF	3CF	4CF	6CF	6CF
	1700	1CF	2CF	3CF	3CF	4CF	6CF	6CF
	1800	1CF	2CF	3CF	3CF	4CF	6CF	6CF
	1900	2CF	2CF	3CF	3CF	4CF	6CF	6CF
	2000	2CF	2CF	3CF	3CF	4CF	6CF	6CF
	2100	2CF	2CF	3CF	3CF	4CF	6CF	6CF
	2200	2CF	2CF	3CF	3CF	4CF	6CF	6CF
	2225	6CF	6CF	6CF	6CF	6CF	6CF	6CF

Similar CDA selection mode tables were determined for the TM-1 and TM-2 engine calibrations using different selection criteria. For example, since TM-1 and TM-2 are used when the SCR temperature is low, the turbine-out temperature had higher priority than CO_2. However, the state machine implemented for this project allowed two CDA maps for TM-1, TM-1a (or Mode 1) and TM-1b (or Mode 2). During a cold-start (coolant temperature < 40°C), the state machine starts in TM-1a until the SCR bed temperature increases above a threshold after which the mode changes to TM-1b. Therefore, for TM-1a, the priority for CDA mode selection was exhaust enthalpy with 4CF being initially chosen above 1100 rpm. However, transient testing with both CDA and no CDA during TM-1a showed faster AT warm-up without CDA due to the higher

exhaust enthalpy of 6CF operation so the final CDA-R map for TM1a was only 6CF. The CDA-R tables for the thermal management modes are shown in Table 12 through Table 14.

TABLE 12. CDA-R TABLE FOR PACKAGE 2 TM-2 (MODE 3)

Approx BMEP, bar		0	1	1.5	2	3	3.5	4
	800	3CF	3CF	3CF	3CF	6CF	6CF	6CF
	850	3CF	3CF	3CF	3CF	6CF	6CF	6CF
	900	1CF	3CF	3CF	3CF	6CF	6CF	6CF
	1000	1CF	3CF	3CF	3CF	3CF	6CF	6CF
	1100	1CF	3CF	3CF	3CF	3CF	6CF	6CF
	1200	1CF	2CF	2CF	3CF	4CF	6CF	6CF
Speed, rpm	1300	1CF	2CF	2CF	3CF	4CF	6CF	6CF
	1400	1CF	2CF	3CF	3CF	4CF	6CF	6CF
	1500	1CF	2CF	3CF	3CF	4CF	6CF	6CF
	1600	1CF	2CF	3CF	3CF	4CF	6CF	6CF
	1700	1CF	2CF	3CF	3CF	4CF	6CF	6CF
	1800	1CF	2CF	3CF	3CF	4CF	6CF	6CF
	1900	2CF	2CF	3CF	3CF	4CF	6CF	6CF
	2000	2CF	2CF	3CF	3CF	4CF	6CF	6CF
	2100	2CF	2CF	3CF	3CF	4CF	6CF	6CF
	2200	2CF	2CF	3CF	3CF	4CF	6CF	6CF
	2225	6CF	6CF	6CF	6CF	6CF	6CF	6CF

TABLE 13. CDA-R TABLE FOR PACKAGE 2 TM-1B (MODE 2)

Approx BMEP, bar		0	1	1.5	2	3	3.5	4
	800	3CF	3CF	3CF	3CF	6CF	6CF	6CF
	850	3CF	3CF	3CF	3CF	6CF	6CF	6CF
	900	1CF	3CF	3CF	3CF	3CF	6CF	6CF
	1000	1CF	3CF	3CF	3CF	3CF	6CF	6CF
	1100	1CF	3CF	3CF	3CF	3CF	6CF	6CF
	1200	1CF	2CF	3CF	3CF	3CF	6CF	6CF
Speed, rpm	1300	1CF	2CF	3CF	3CF	3CF	6CF	6CF
	1400	1CF	2CF	3CF	3CF	3CF	6CF	6CF
	1500	1CF	2CF	3CF	3CF	3CF	6CF	6CF
	1600	1CF	2CF	3CF	3CF	3CF	6CF	6CF
	1700	1CF	2CF	3CF	3CF	3CF	6CF	6CF
	1800	1CF	2CF	3CF	3CF	3CF	6CF	6CF
	1900	1CF	2CF	3CF	3CF	3CF	6CF	6CF
	2000	1CF	2CF	3CF	3CF	3CF	6CF	6CF
	2100	1CF	2CF	3CF	3CF	3CF	6CF	6CF
	2200	1CF	2CF	3CF	3CF	3CF	6CF	6CF
	2225	6CF	6CF	6CF	6CF	6CF	6CF	6CF

TABLE 14. CDA-R TABLE FOR PACKAGE 2 TM-1A (MODE 1)

Approx BMEP, bar		0	1	1.5	2	3	3.5	4
	800	6CF	6CF	6CF	6CF	6CF	6CF	6CF
	850	6CF	6CF	6CF	6CF	6CF	6CF	6CF
	900	6CF	6CF	6CF	6CF	6CF	6CF	6CF
	1000	6CF	6CF	6CF	6CF	6CF	6CF	6CF
	1100	6CF	6CF	6CF	6CF	6CF	6CF	6CF
	1200	6CF	6CF	6CF	6CF	6CF	6CF	6CF
Speed, rpm	1300	6CF	6CF	6CF	6CF	6CF	6CF	6CF
	1400	6CF	6CF	6CF	6CF	6CF	6CF	6CF
	1500	6CF	6CF	6CF	6CF	6CF	6CF	6CF
	1600	6CF	6CF	6CF	6CF	6CF	6CF	6CF
	1700	6CF	6CF	6CF	6CF	6CF	6CF	6CF
	1800	6CF	6CF	6CF	6CF	6CF	6CF	6CF
	1900	6CF	6CF	6CF	6CF	6CF	6CF	6CF
	2000	6CF	6CF	6CF	6CF	6CF	6CF	6CF
	2100	6CF	6CF	6CF	6CF	6CF	6CF	6CF
	2200	6CF	6CF	6CF	6CF	6CF	6CF	6CF
	2225	6CF	6CF	6CF	6CF	6CF	6CF	6CF

3.3.2.2. DSF Calibration

The DSF algorithm was provided by Tula as a protected control model which was incorporated into the supervisory controller. A flag in the software was added to enable switching between CDA-R or DSF implementations when CDA operation was desired. The DSF block required a set of inputs including engine speed, desired torque, and current cylinder number and had several calibration settings and flags. The outputs from the DSF block were used by the supervisory controller to control cylinder specific CDA solenoid valves and fueling during DSF operation. The main differences between CDA-R and DSF were how and when the patterns are selected, the number of available patterns, and how the pattern transitions were handled during speed and load changes. DSF uses firing fractions (i.e., 0.5 = ½ engine CDA) instead of discrete CDA modes so direct table interpolation is used as the engine speed and load change. The CDA-R implementation has a persistence timer (nominally 1.5 sec) which prevents going into CDA until the operation (engine speed and fueling) has resided in the CDA area for that amount of time while DSF has no delay. In addition to the fixed CDA modes examined for the CDA-R calibration, the DSF pattern library has several hybrid and rotating patterns that vary which cylinders are deactivated and take multiple engine cycles to complete. With these difference in mind, the DSF calibration will be reviewed.

The methodology used for the DSF calibration was similar to the one used for CDA-R. At a given engine speed and load, the DSF pattern, or firing fraction (FF), was varied from the available set to determine the FF that gave the lowest CO_2 (for FE map) or highest exhaust temperature (for TM-1 and 2 maps) with acceptable NO_X and smoke emissions. However, early in

the DSF FE calibration effort, considerable scatter between FF and CO_2 was observed as shown in Figure 48. After further review, a clearer trend could be seen if the DSF data were separated into fixed and rotating patterns as shown in Figure 49, where an FF of 0.5 gave the lowest CO_2. The CO_2 for the rotating patterns was considerably higher and more variable than the fixed patterns. The root cause of this was found to be a lack of refire combustion robustness of the test engine. A refire means injecting fuel for combustion on the cycle immediately after a deactivated or skipped cycle so no intake event occurs to replenish the cylinder charge. In Tula's experience, refire combustion robustness varies amongst engines with some capable of skipping multiple cycles while others cannot skip one cycle without a recharge, which was the case for the test engine in this program. Factors that affect refire include blowby, in-cylinder cooling, injection pattern, and compression ratio. To illustrate the behavior observed on the test engine, cylinder pressure and injection current for three consecutive cycles is shown in Figure 50. Cycle 3 represents normal combustion, cycle 4 is a skip, and cycle 5 is a refire. The combustion for cycle 5 is noticeably weaker than cycle 3 causing reduced fuel consumption. Due to this engine characteristic, only fixed FF patterns were screened for the DSF calibration.

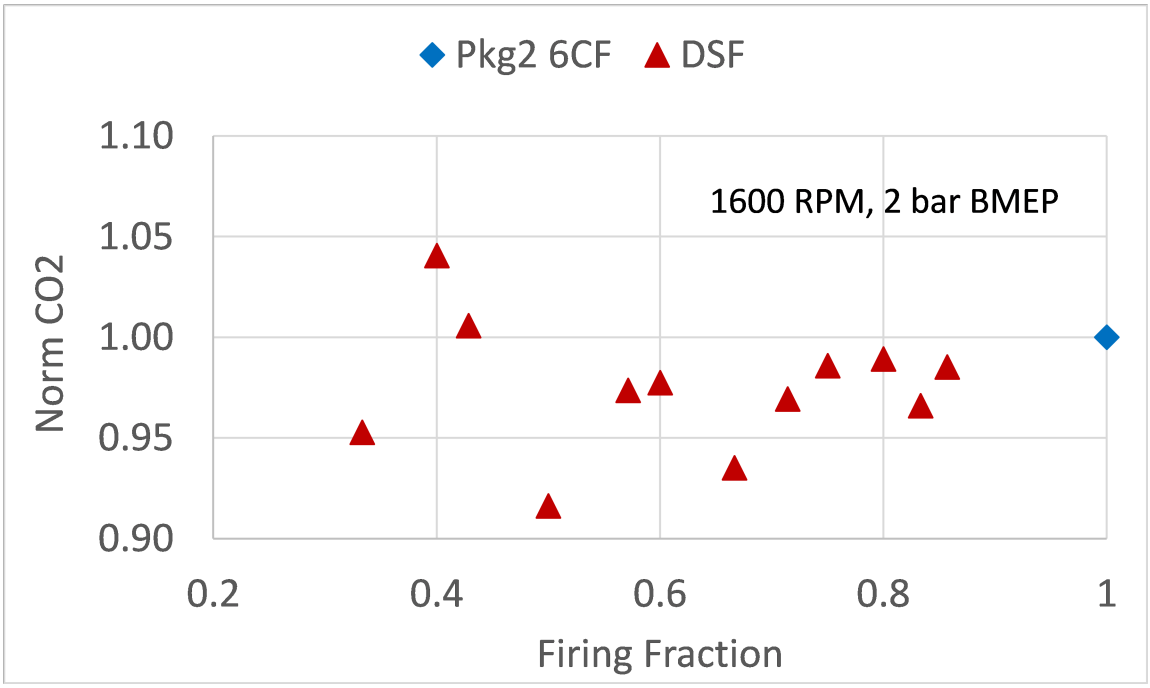


FIGURE 48. DSF FIRING FRACTION VERSUS CO2 AT 1600 RPM AND 2 BAR BMEP SHOWING NO CLEAR TREND

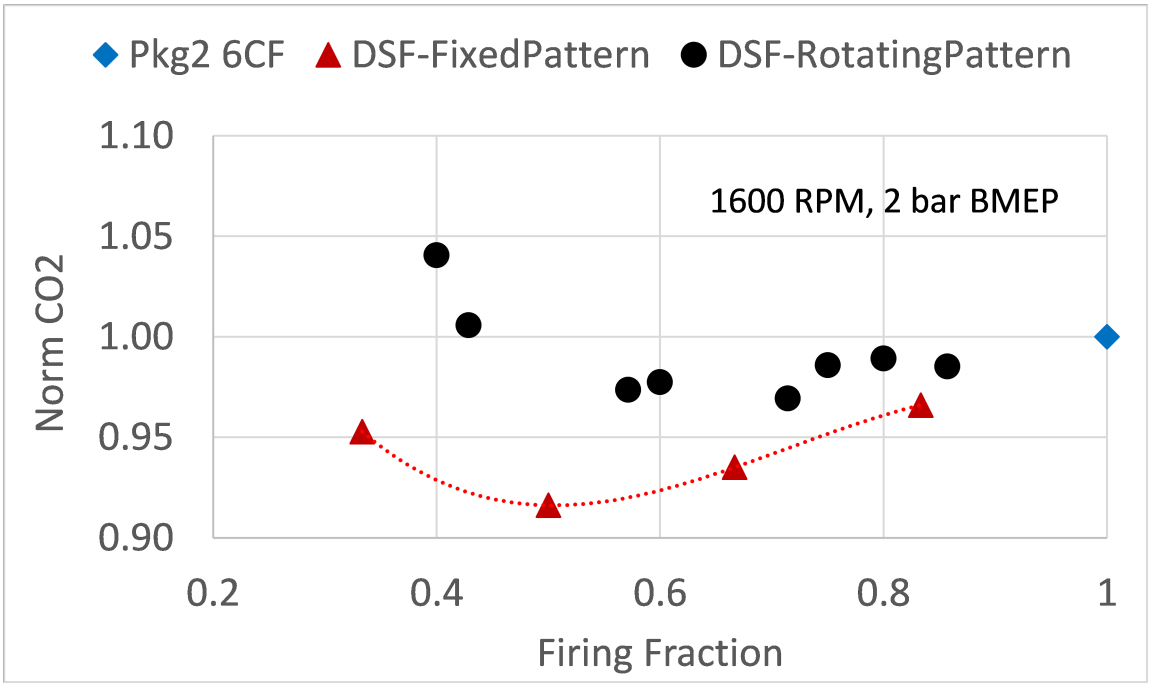


FIGURE 49. CLEAR TREND OBSERVED AT 1600 RPM AND 2 BAR BMEP FOR FIXED DSF PATTERNS

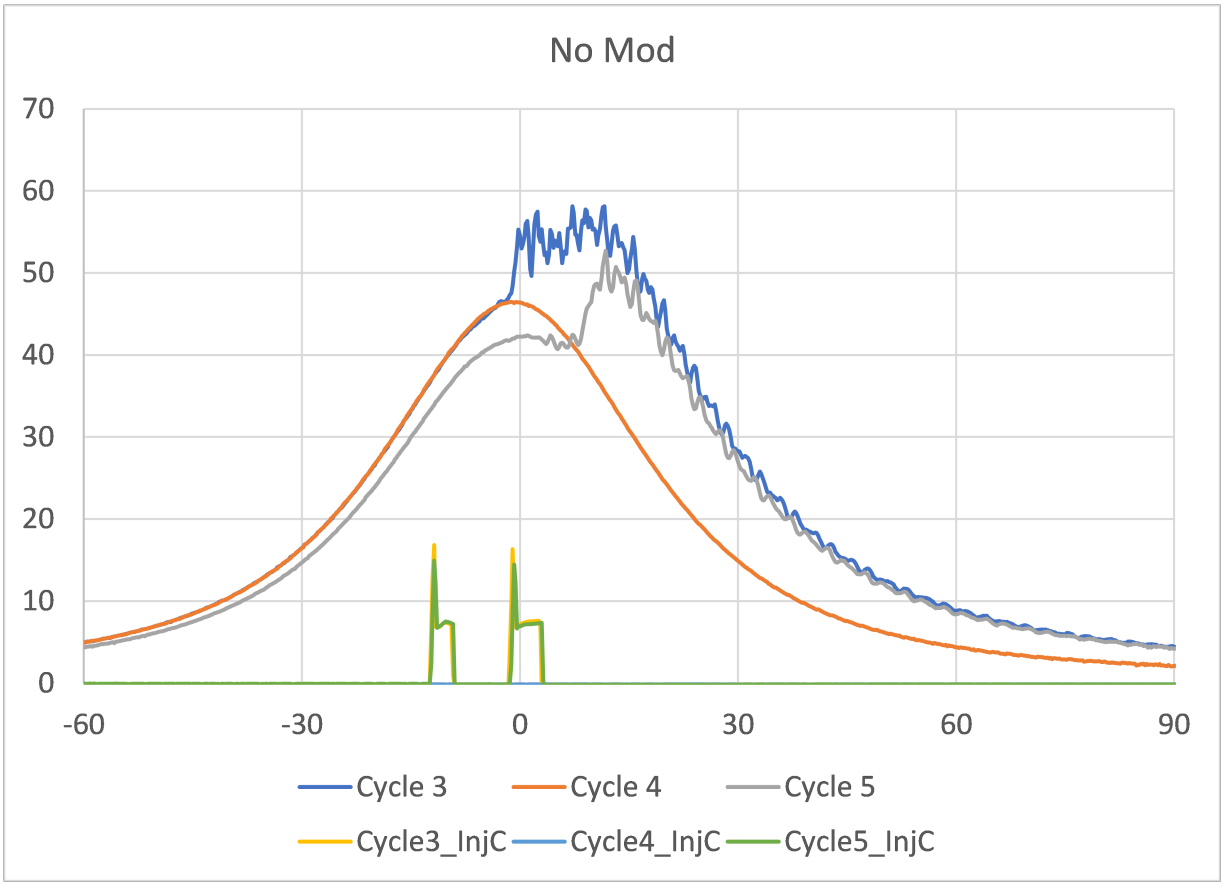


FIGURE 50.EXAMPLE OF POOR REFIRE COMBUSTION IN CYCLE 5

Following the same methodology for other engine speed and loads, DSF FF maps were determined for the FE, TM-2, and TM-1b engine modes as shown in Figure 51 through Figure 54. As mentioned before, only 6CF or FF=1 was used for TM-1a mode.

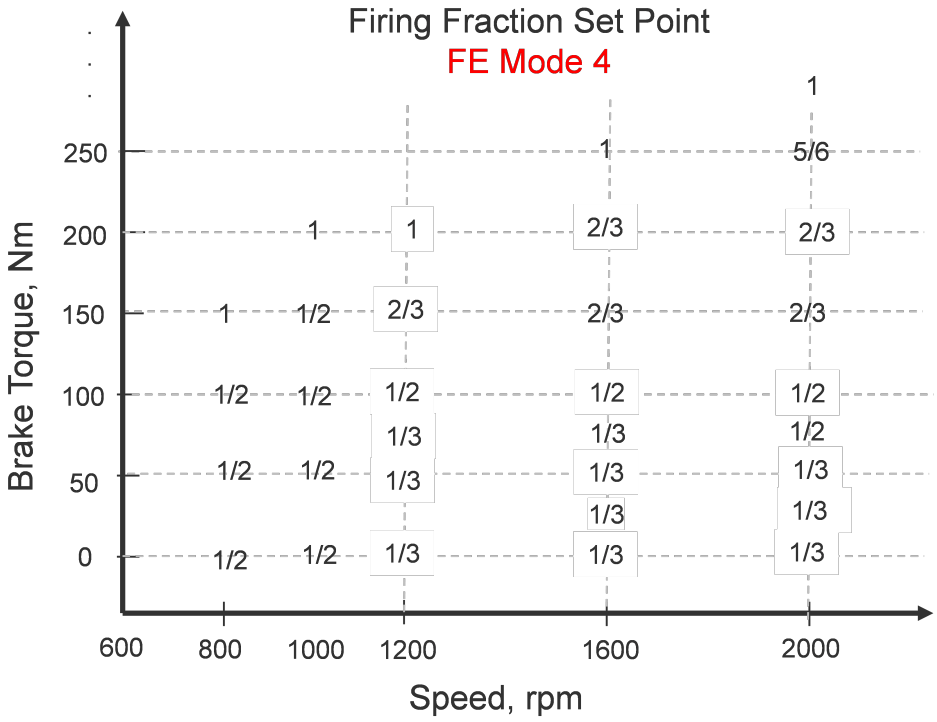


FIGURE 51. DSF FIRING FRACTION MAP FOR FE MODE 4

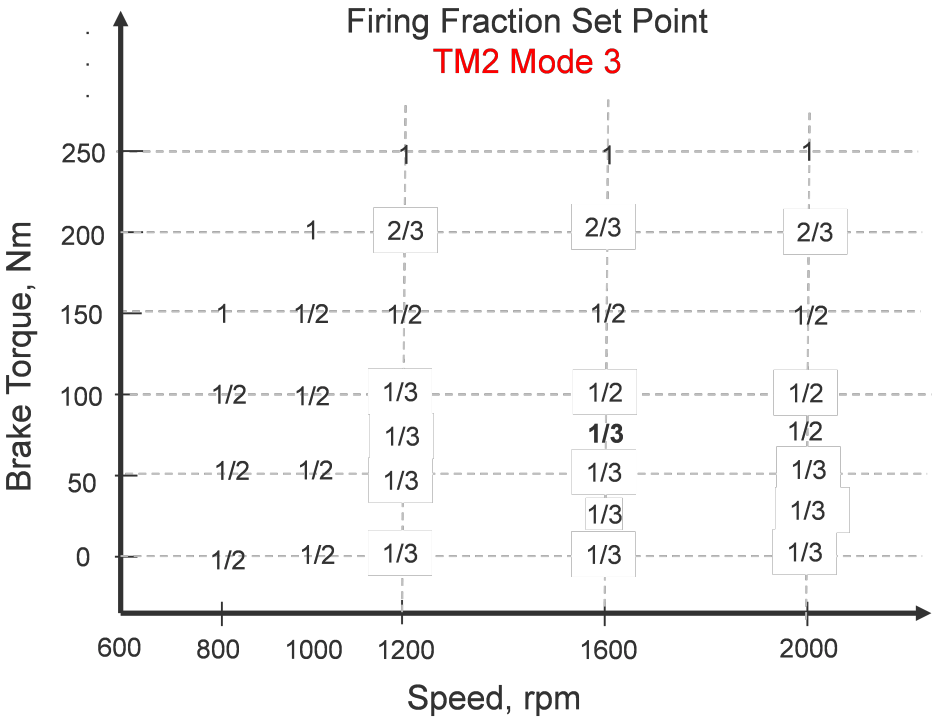


FIGURE 52. DSF FIRING FRACTION MAP FOR TM2 MODE 3

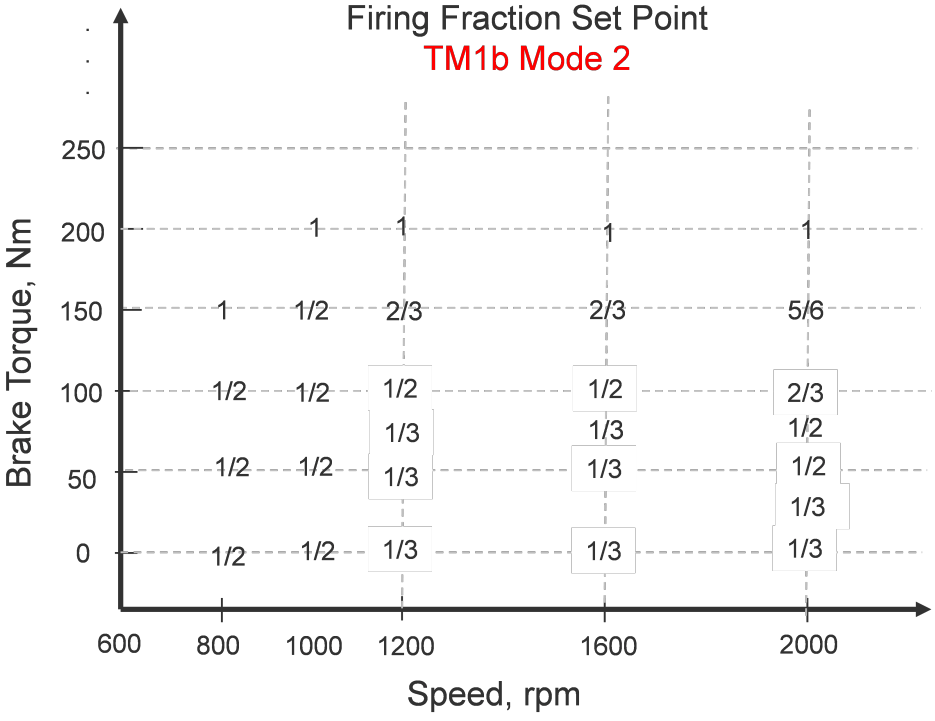


FIGURE 53. DSF FIRING FRACTION MAP FOR TM1B MODE 2

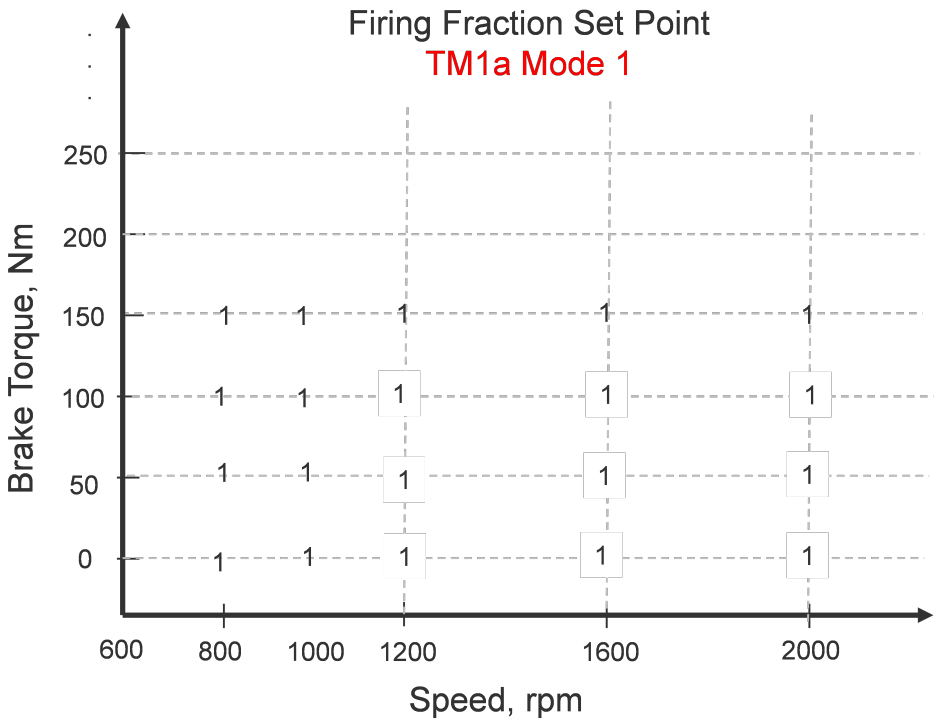


FIGURE 54. DSF FIRING FRACTION MAP FOR TM1A MODE 1

3.3.2.3. Transient Evaluations of Package 2 Calibrations

In this section, transient results obtained with the various Package 2 calibrations and baseline AT system over the test cycles of interest are presented.

3.3.3.1. Cold-start NRTC Test Results

The same state machine that was used for the Package 1 calibration was used for the Package 2 evaluations. As a reminder, the Package 2 calibration differs from Package 1 in the following ways:

1. Modified FE calibration with advanced injection timing and higher engine-out NO_X for reduced fuel consumption
2. Separate CDA mode calibrations for TM-1b, TM-2 and FE for both CDA-R and DSF

Cold-start NRTC results for Package 2 calibrations without CDA, with CDA-R, and with DSF, are shown in Figure 55. The number of active cylinders indicates when CDA is active where a value of 6 is no CDA, 4 is 4CF or 2/3 FF, 3 is 3CF or 1/2 FF, and 2 is 2CF or 1/3 FF. Comparing the two CDA cases, the effect of the persistence timer for CDA-R is clear with considerably more CDA activity for DSF. In general, higher turbine-out and SCR bed temperatures can be observed for the DSF calibration. In addition, the combination of reduced exhaust flow rate and increased

exhaust temperature associated with CDA (both CDA-R and DSF) prevents the SCR bed temperature from falling below 300°C between 900 and 1100 seconds.

To better assess the impact of the various CDA calibrations on aftertreatment warm-up, only the first 400 seconds of the cold NRTC are shown in Figure 56. Vertical dashed lines are included to indicate where the engine control mode changes for the no CDA case. As expected, the change from TM-1a to TM-1b (control mode 1 to 2) occurs at the same time for all cases. However, a slight delay in changing from TM-1b to TM-2 (control mode 2 to 3) can be observed for DSF which can be attributed to lower exhaust enthalpy during the more frequent CDA operation. However, as the aftertreatment warms, exhaust temperature begins to dominate and the switch to the FE mode occurs first for DSF.

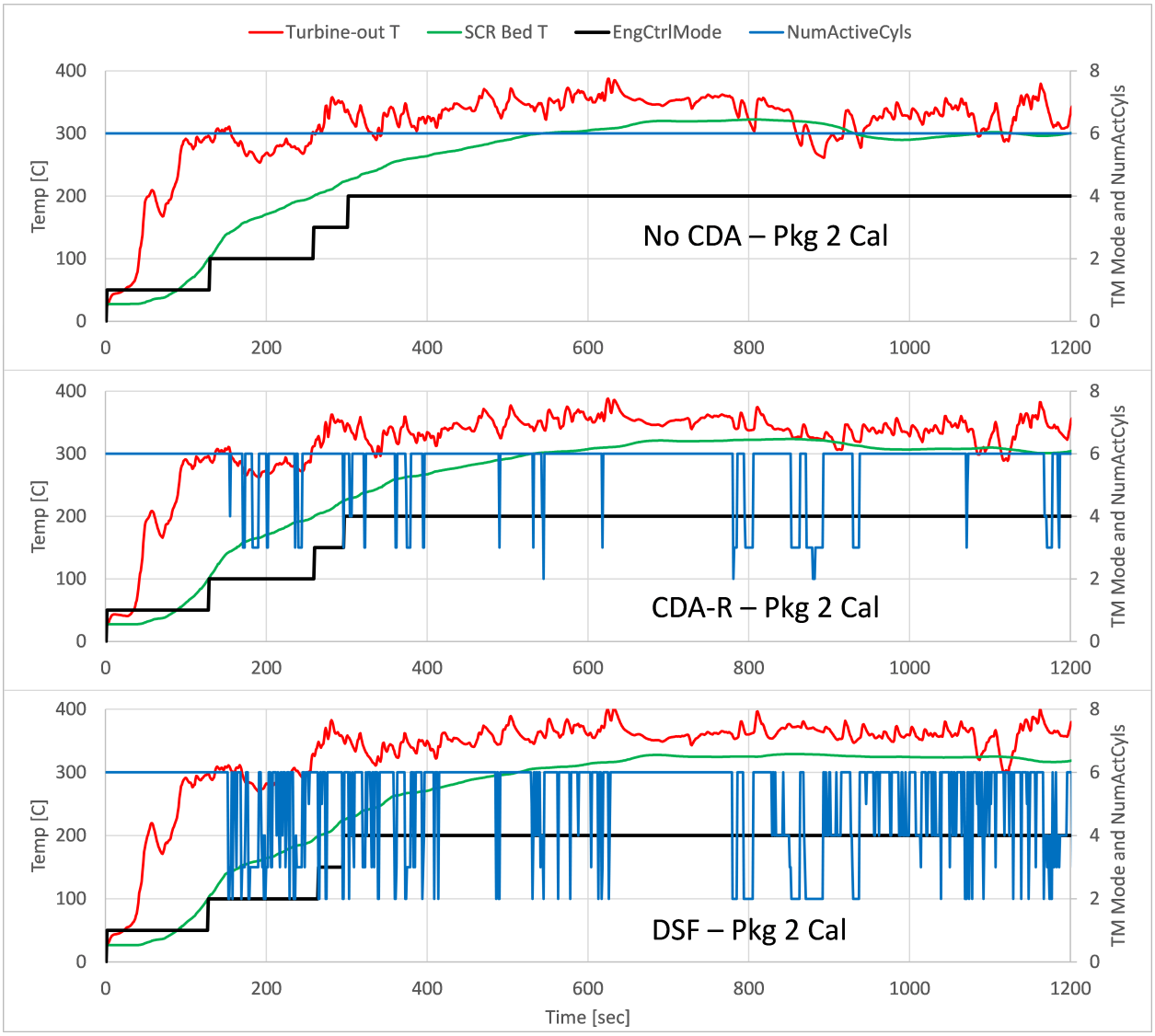


FIGURE 55. COLD-START NRTC RESULTS WITH PACKAGE 2 CALIBRATIONS

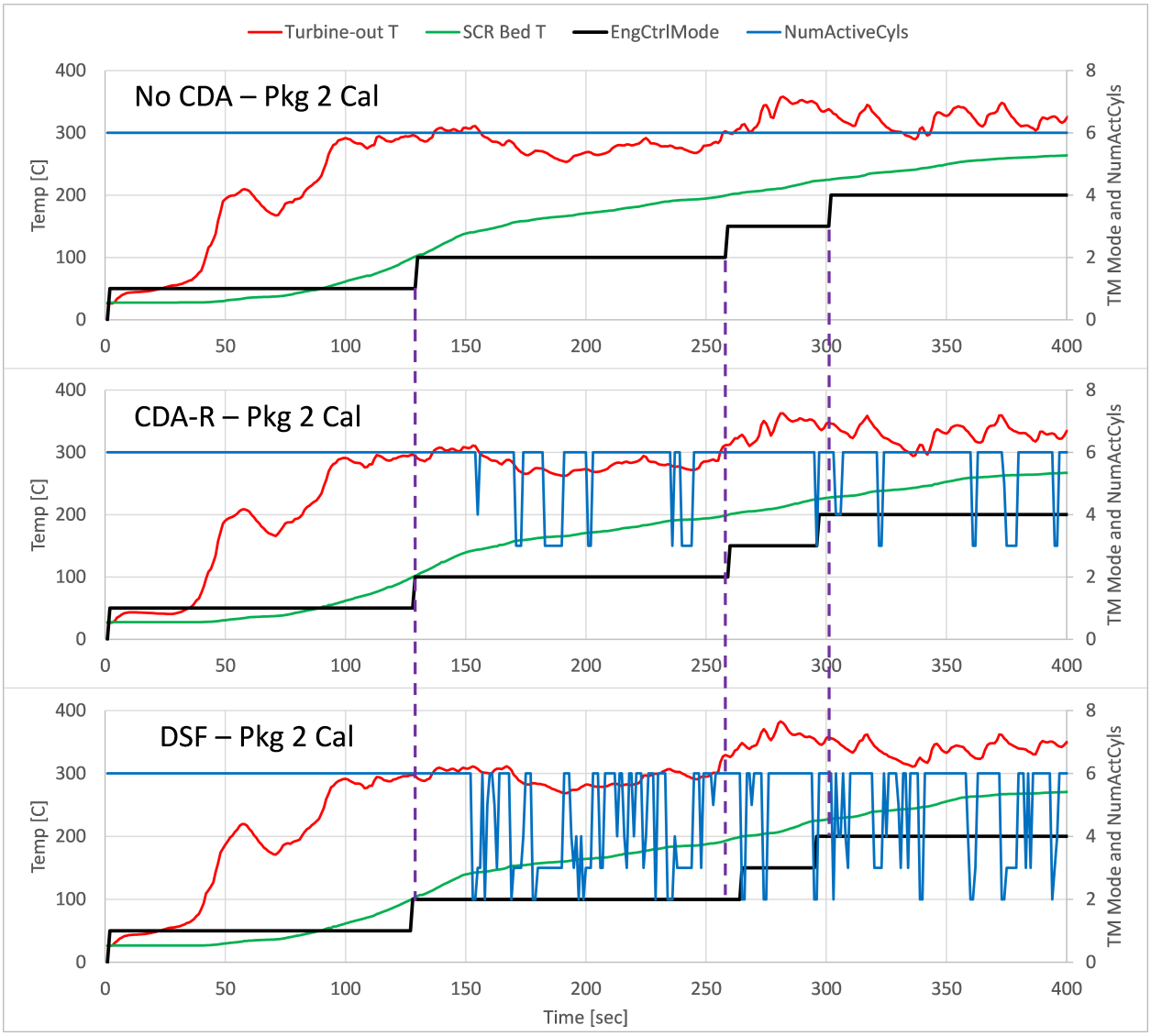


FIGURE 56. FIRST 400 SECONDS OF COLD-START NRTC RESULTS WITH PACKAGE 2 CALIBRATIONS

3.3.3.2. Hot-start NRTC Test Results

Hot-start NRTC results are shown in Figure 57. As for the cold-start results, vertical dashed lines are provided to indicate when the engine control modes changed for the no CDA case. Both CDA calibrations changed from TM-1b to TM-2 faster than the no CDA case, but the DSF case changed to the FE mode the fastest due to more frequent CDA operation with higher exhaust temperatures. In addition, the DSF case had the highest overall temperatures.

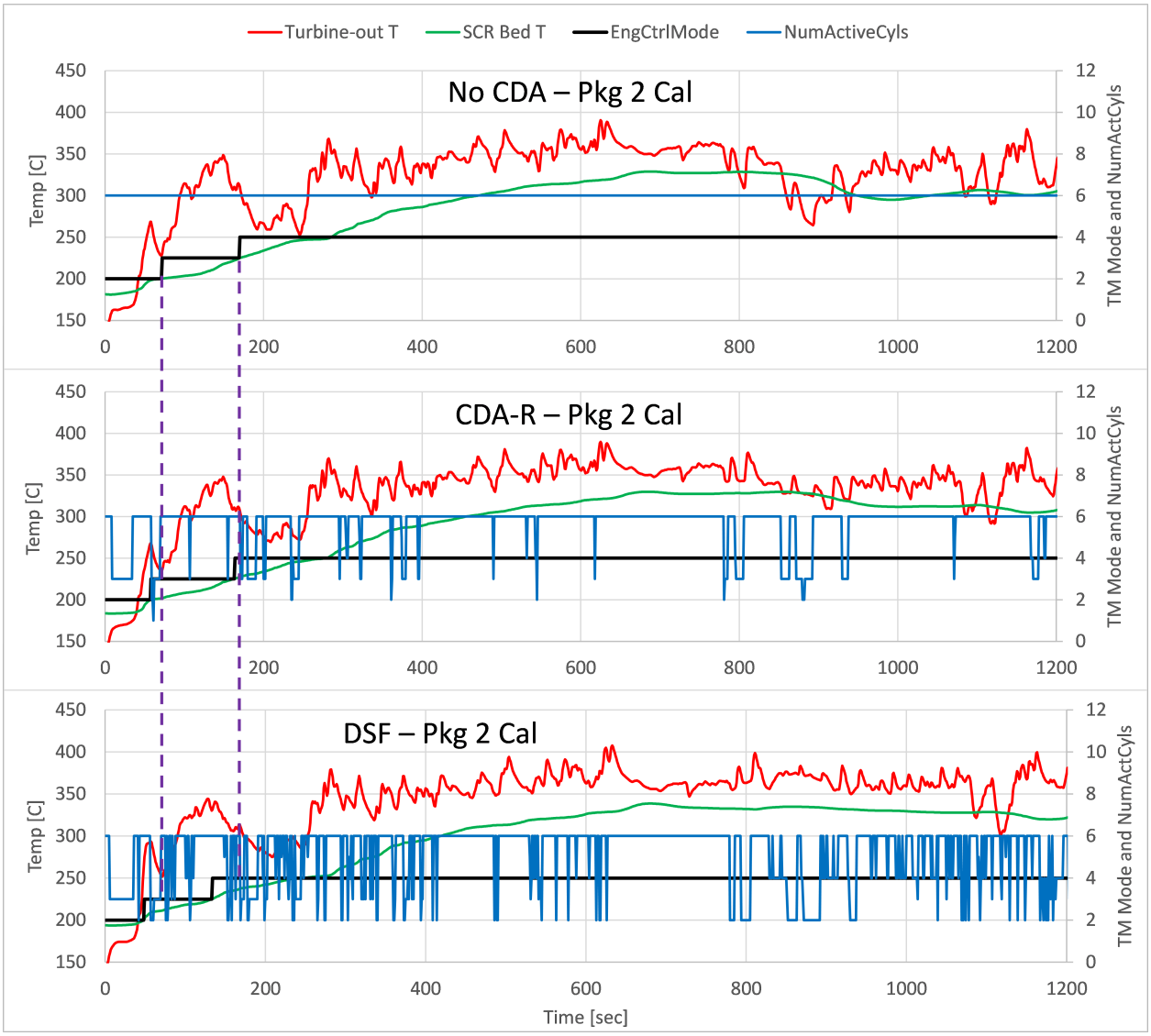


FIGURE 57. HOT-START NRTC RESULTS WITH PACKAGE 2 CALIBRATIONS

3.3.3.3. LLAC Test Results

Engine speed and torque results for the LLAC are shown in Figure 58. Besides prolonged low load operation in the middle section of the cycle, three long idle segments are included where significant cooling of the aftertreatment can occur. The use of CDA was expected to reduce the amount of cooling during these segments.

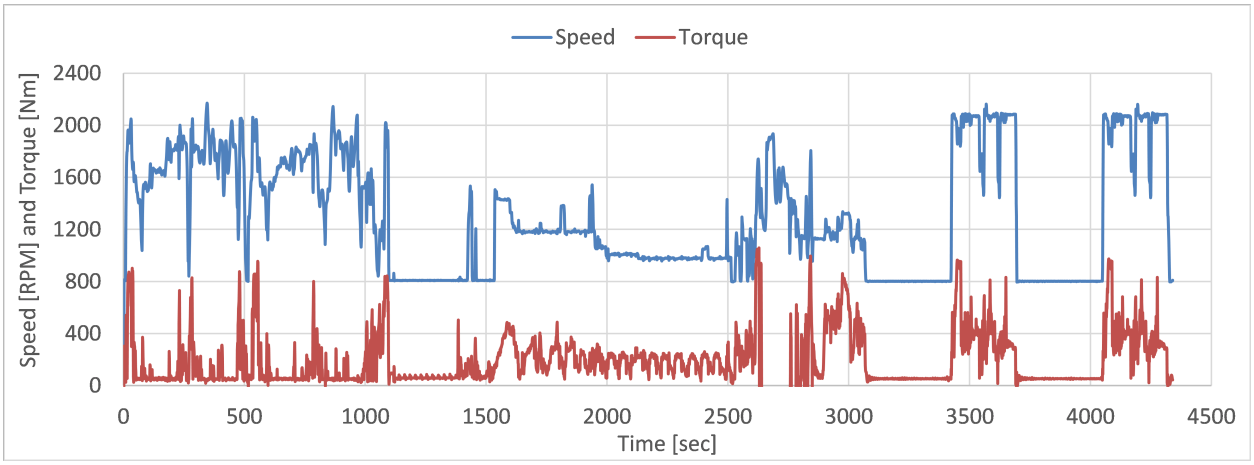


FIGURE 58. SPEED AND TORQUE TRACES FOR LLAC

Turbine-out and SCR bed temperature traces for the three CDA cases are shown in Figure 59. As expected, the use of CDA reduced the amount of SCR cooling during the low load and extended idle segments with both CDA-R and DSF preventing the SCR bed temperature from falling below 200°C which is significant for maintaining high NO_X conversion efficiency. DSF provided the highest SCR bed temperature due to more frequent CDA operation. The corresponding number of active cylinders and thermal management modes are shown in Figure 60. As shown, the biggest impact of CDA was preventing the control mode from going into the more aggressive and fuel inefficient TM-1b thermal management mode 2. Other notable observations are the lack of CDA in the latter part of the cycle for CDA-R due to the persistence timer and the fact that the CDA-R calibration included 1CF operation during fuel cut while DSF did not. This was due to the difference in the inputs to look up the CDA mode where CDA-R used desired fuel (which included 0 for fuel cut) while DSF used desired torque which was limited to 0 Nm.

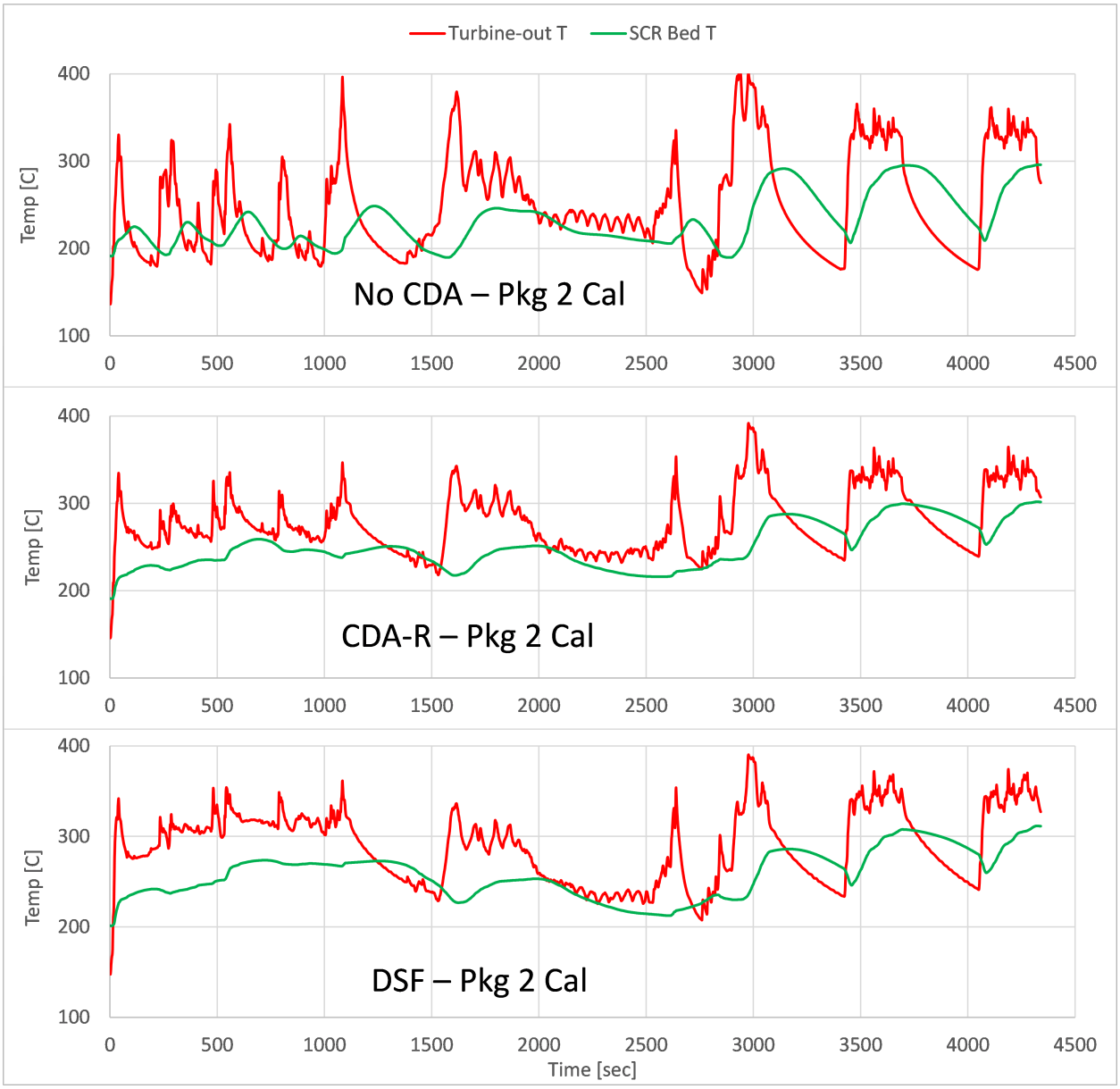


FIGURE 59. TURBINE-OUT AND SCR BED TEMPERATURE RESULTS FOR LLAC WITH PACKAGE 2 CALIBRATIONS

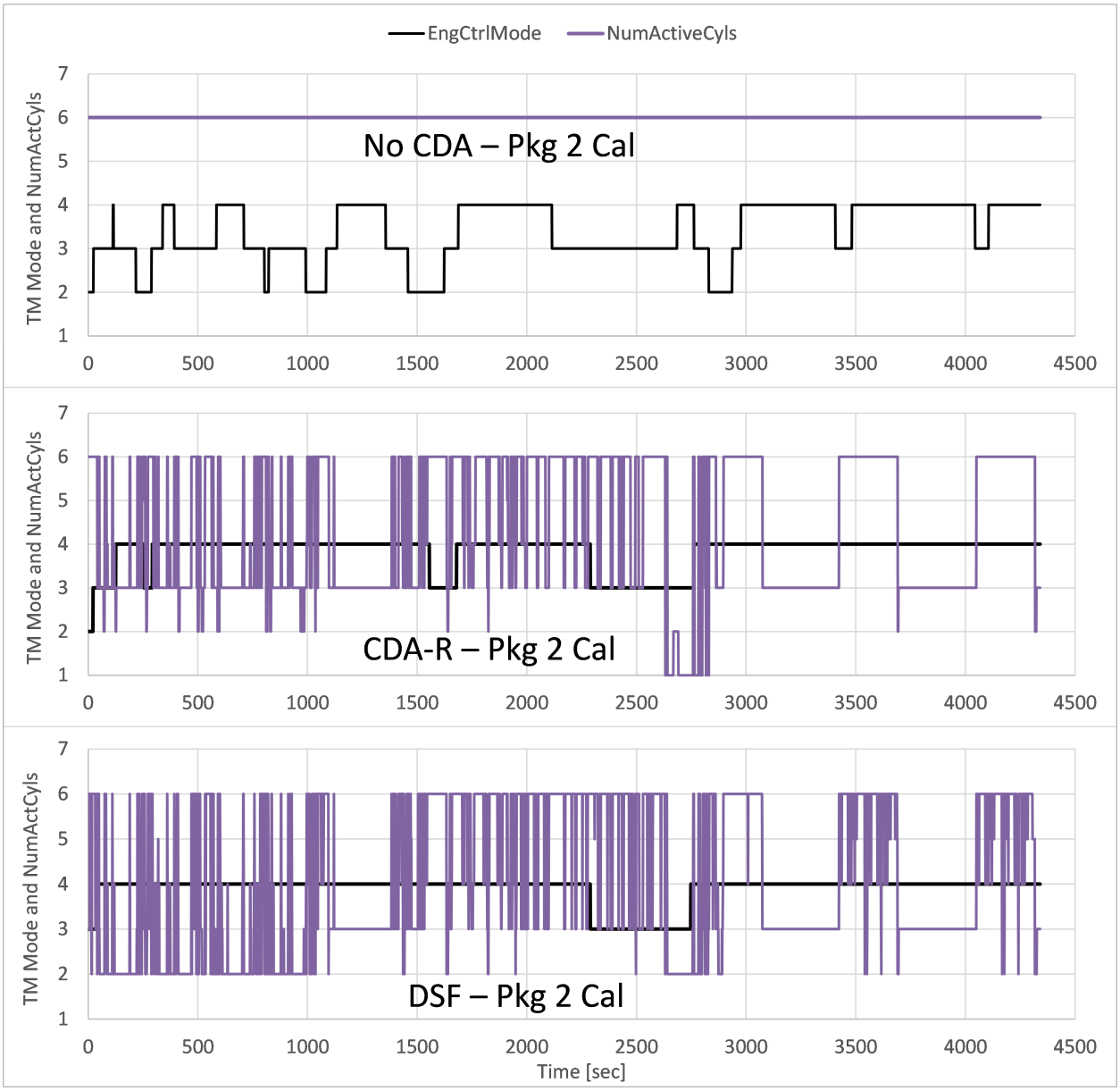


FIGURE 60. ENGINE CONTROL MODE AND NUMBER OF ACTIVE CYLINDERS FOR LLAC WITH PACKAGE 2 CALIBRATIONS

3.3.3.4. RMC Test Results

Engine speed and torque results for the RMC are shown in Figure 61. As shown, most of the RMC operates above the 200 Nm limit for CDA except for the idle and rated speed, 10% load (2200 rpm, 77 Nm) points. Therefore, the majority of the CO_2 reduction for the RMC was expected to come from the revised FE calibration.

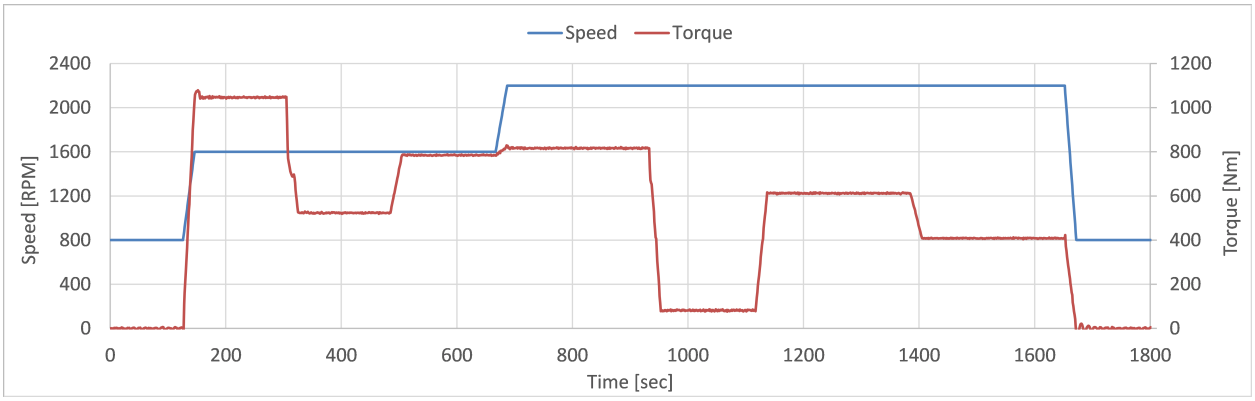


FIGURE 61. SPEED AND TORQUE TRACES FOR RMC

Turbine-out and SCR bed temperature traces along with engine control mode and number of active cylinders for the three CDA cases are shown in Figure 62. Due to the high load operation of the RMC, the SCR bed temperature remains high enough that the engine control mode remains in FE (engine control mode 4) for the entire cycle. The effects of CDA on reducing SCR cooling can be seen in the first idle segment for both turbine-out and SCR bed temperature. Notable differences between the two CDA calibrations can be seen for the rated speed, 10% load point where different CDA modes were used. For CDA-R, switching between 3 and 4CF operation was observed while fixed 2CF with higher exhaust temperature was used for DSF.

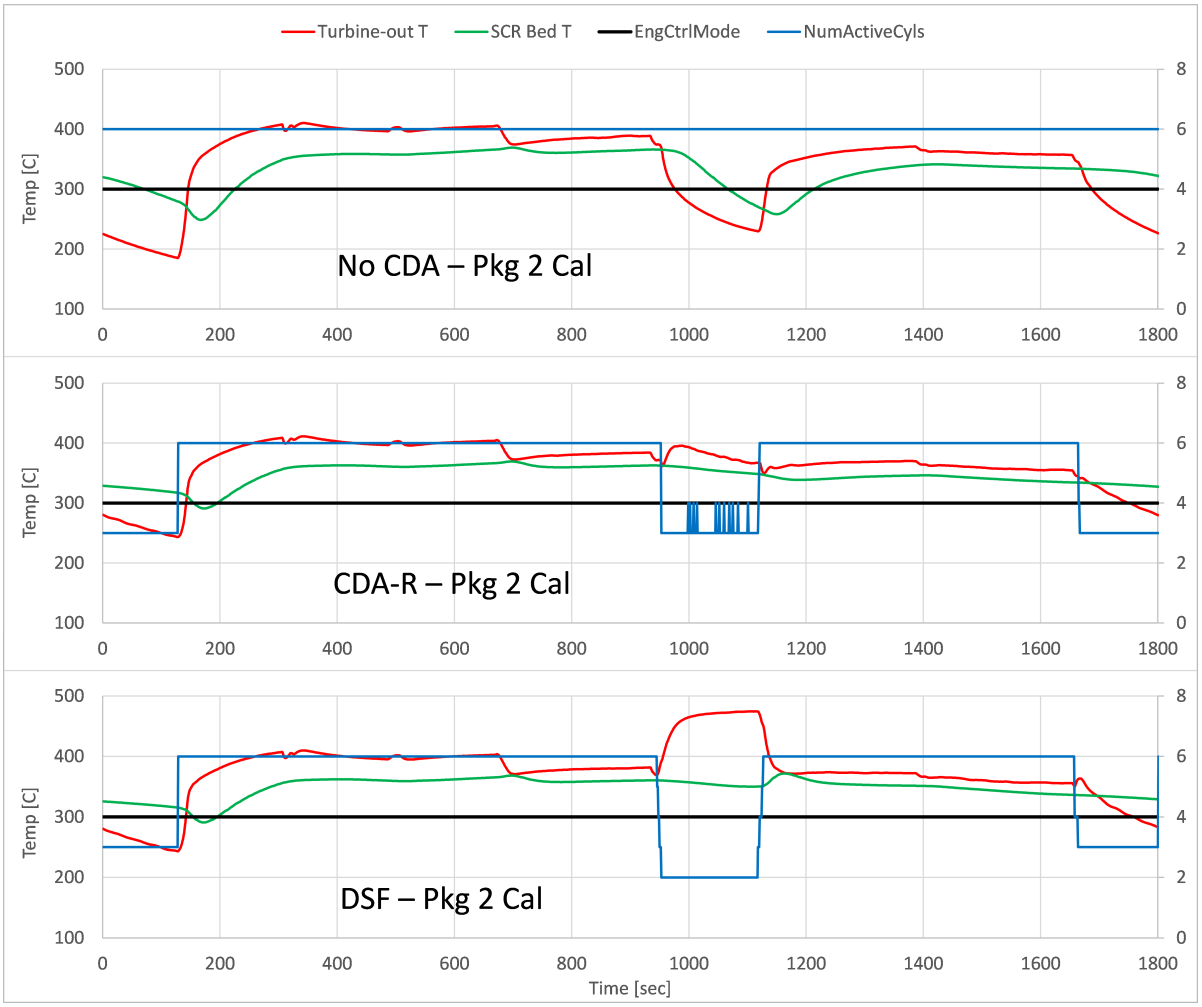


FIGURE 62. RMC RESULTS WITH PACKAGE 2 CALIBRATIONS

3.3.3.5. Summary of Transient Test Results with Base Aftertreatment System

A summary of the Package 2 calibration results along with the baseline for comparison purposes are provided in this section. Cold-start NRTC performance metrics are listed in Table 15 while Table 16 contains results from all test cycles and includes the baseline for reference. This data is shown graphically in Figure 63 through Figure 65.

TABLE 15. COLD-START NRTC PERFORMANCE COMPARISON FOR PACKAGE 2 CALIBRATIONS

		No CDA	CDA-R	DSF
Run #		6571	6563	6594
$t_{200°C}$ (Time to 200°C SCR Bed T)	sec	259	260	265
Cumulative Engine-out $BSNO_X$ at $t_{200°C}$	g/kW-hr	0.28	0.28	0.29
Cumulative Tailpipe $BSNO_X$ at $t_{200°C}$	g/kW-hr	0.18	0.18	0.17
Cycle Tailpipe $BSNO_X$	g/kW-hr	0.23	0.23	0.21
Cycle $BSCO_2$	g/kW-hr	747	742	734

TABLE 16. TABULAR EMISSIONS PERFORMANCE SUMMARY FOR BASELINE AND PACKAGE 2 CALIBRATIONS

	Calibration	Base	Pkg2 – No CDA	Pkg2 – CDA-R	Pkg2 – DSF
Engine-out $BSNO_X$ [g/kW-hr]	cNRTC	3.15	2.44	2.45	2.57
	hNRTC	2.99	2.46	2.48	2.65
	Composite	3.00	2.46	2.48	2.65
	LLAC	5.26	4.03	4.17	4.34
	RMC	3.11	3.04	2.94	2.87
Tailpipe $BSNO_X$ [g/kW-hr]	cNRTC	0.39	0.23	0.23	0.21
	hNRTC	0.08	0.04	0.03	0.03
	Composite	0.09	0.05	0.04	0.04
	LLAC	1.83	1.44	1.22	1.26
	RMC	0.07	0.06	0.04	0.03
$BSCO_2$ [g/kW-hr]	cNRTC	761	747	742	734
	hNRTC	747	727	721	711
	Composite	748	728	722	712
	LLAC	836	798	760	752
	RMC	697	677	669	668

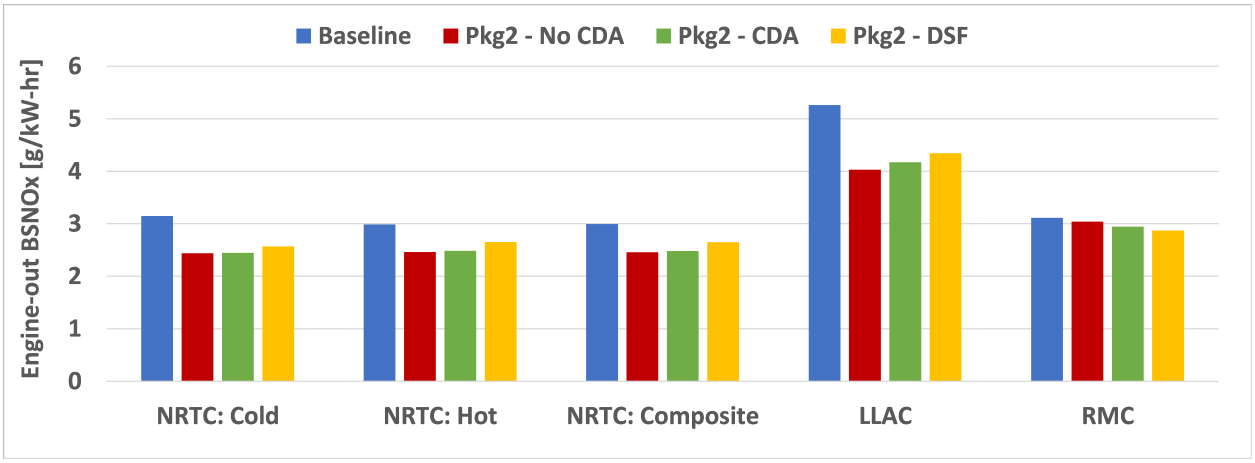


FIGURE 63. ENGINE-OUT $BSNO_X$ EMISSIONS SUMMARY FOR BASELINE AND PACKAGE 2 CALIBRATIONS

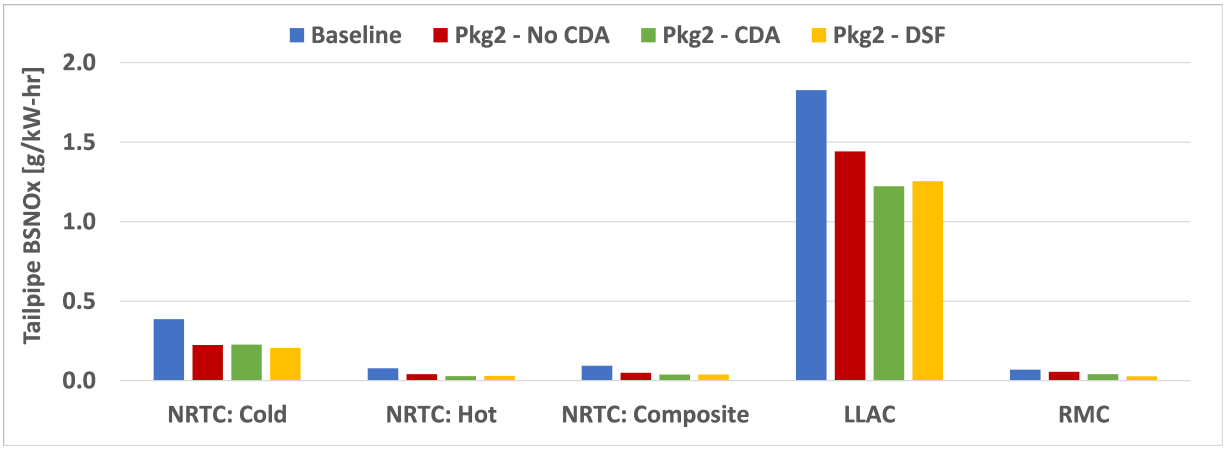


FIGURE 64. TAILPIPE BSNOX EMISSIONS SUMMARY FOR BASELINE AND PACKAGE 2 CALIBRATIONS

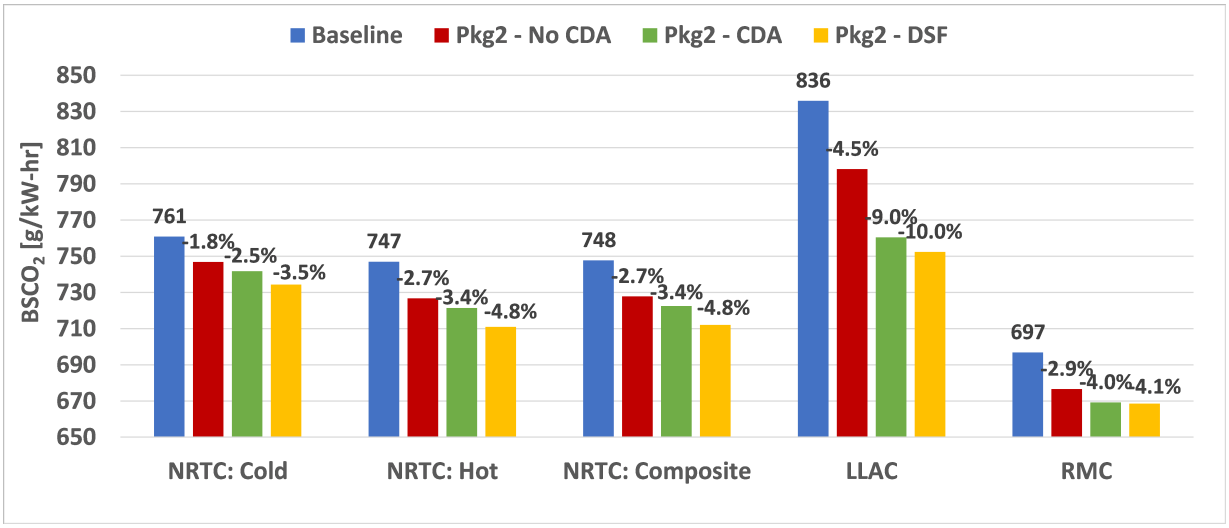


FIGURE 65. BSCO2 EMISSIONS SUMMARY FOR BASELINE AND PACKAGE 2 CALIBRATIONS

3.4 Package 1 Results with Advanced Aftertreatment

For the final stage of this initial program, the modified engine calibrations described earlier were combined with the advanced AT system to demonstrate whether the program targets could be reached by the combined engine-aftertreatment system. It was necessary to wait until both the engine hardware calibrations, aged aftertreatment, and aftertreatment controls were available to examine combined system performance. As a result, one available AT system was chosen for this initial demonstration of capability. It should be noted that continued development under 20MSC005 will evaluate a wider range of engine and aftertreatment options in order to select the final optimal hardware choices for both Package 1 and Package 2.

As a result of these timing limitations, only one advanced AT system teams was chosen for the initial performance evaluation. The Team 2 conventional architecture system was chosen for the initial evaluation, and that system was integrated into the engine exhaust. The installation of the Team 2 system is shown in Figure 66 through Figure 69.



FIGURE 66. FINAL INSTALLATION OF TEAM 2 AFTERTREATMENT SYSTEM

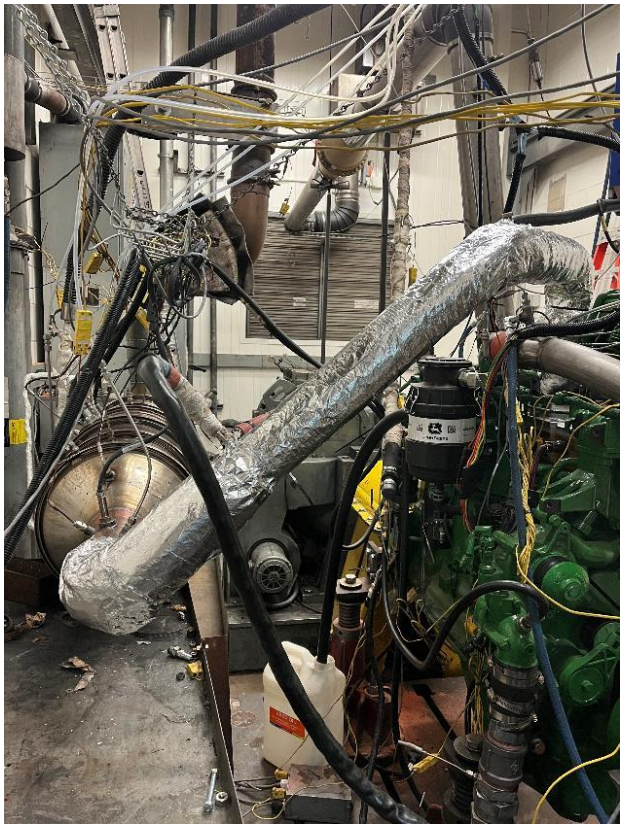


FIGURE 67. AFTERTREATMENT SYSTEM INLET AND TRANSFER TUBE AND INSULATION

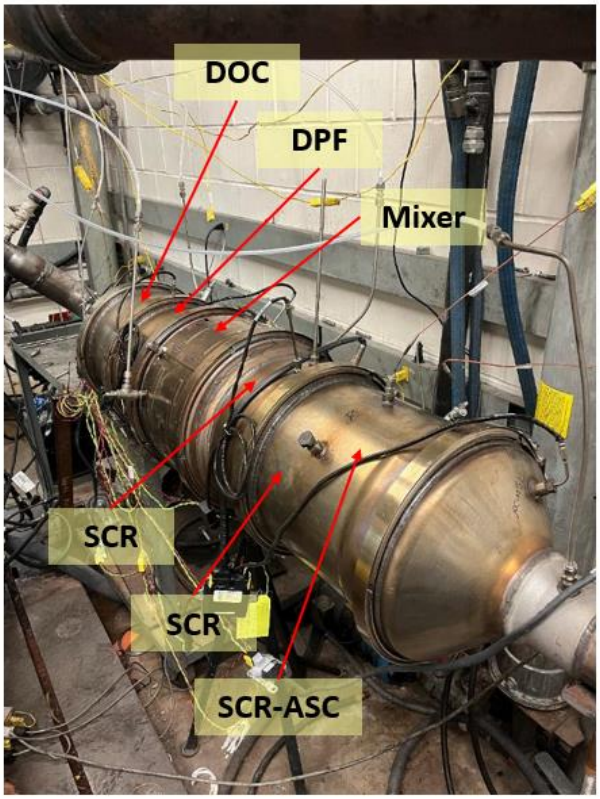


FIGURE 68. AFTERTREATMENT SYSTEM COMPONENTS AS INSTALLED

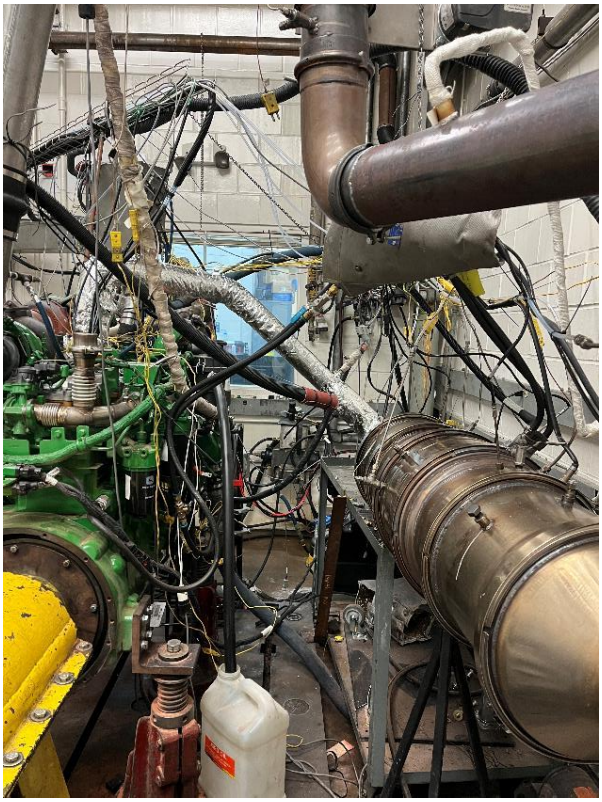


FIGURE 69. AFTERTREATMENT SYSTEM VIEWED FROM OUTLET (SHOWING DEF DOSER AND SENSOR INSTALLATIONS)

The development-aged Team 2 AT system was installed and the aftertreatment controller integration was completed with the associated DOC and SCR model kinetics for that system. Initial performance runs indicated significant performance improvements over the stock AT system, as expected. The initial results indicated cold-NRTC tailpipe NO_X emissions of 0.2 g/kW-hr and hot-NRTC tailpipe NO_X levels on the order of 0.02 g/kW-hr. However, it was clear there was room for further optimization and calibration.

The engine calibration was modified to further reduce engine-out NO_X in crucial in the earliest portions of the cold-start, as shown in Figure 70, which along with adjustments to thermal management and dosing updates, resulted in cold-NRTC emissions of 0.13 g/kW-hr. At the same time, the thermal management strategy and mode switch-points were optimized for better LLAC performance, as shown in Figure 71.

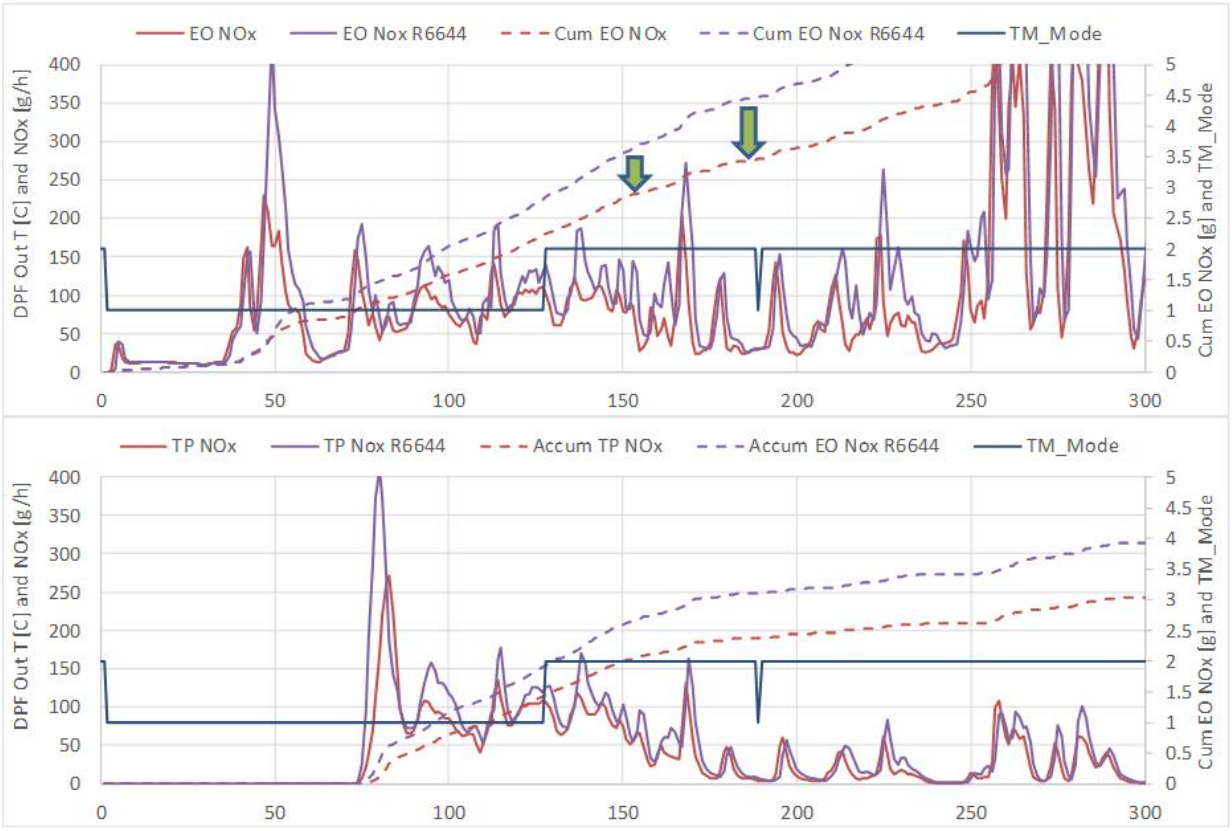


FIGURE 70. IMPROVEMENTS TO COLD-START NRTC CALIBRATION

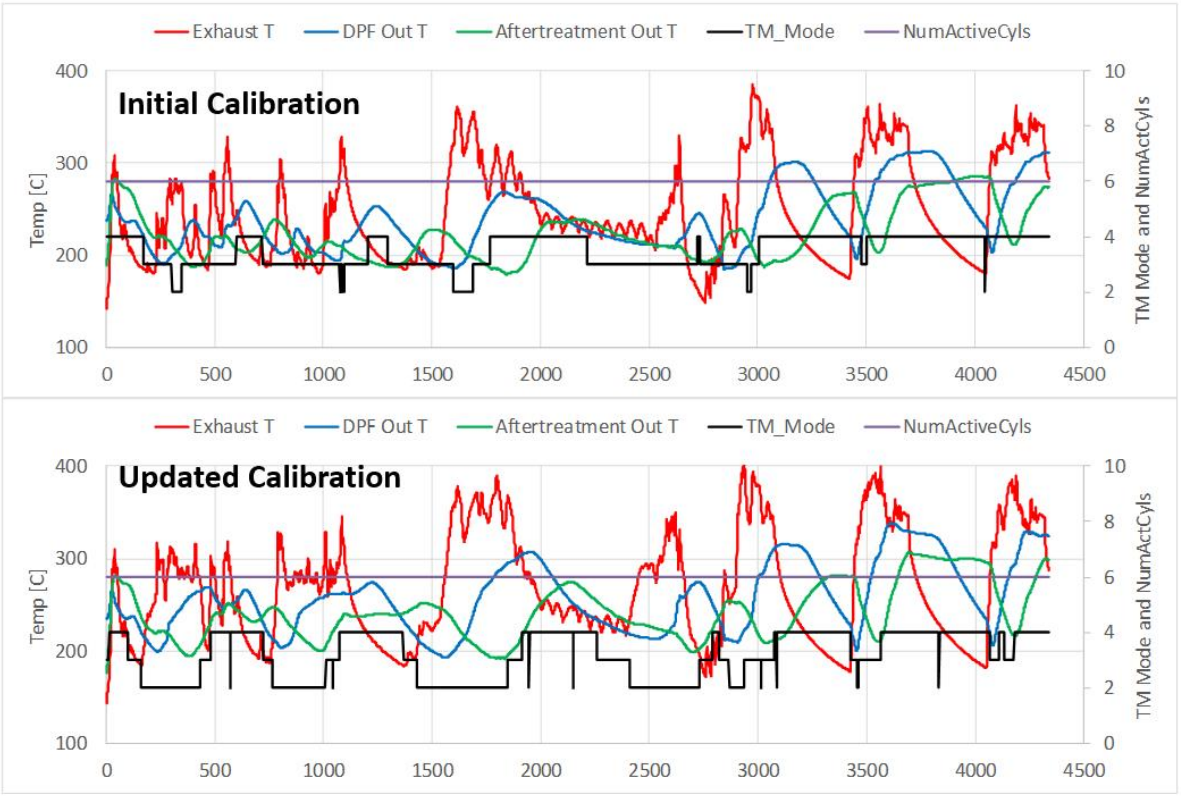


FIGURE 71. THERMAL MANAGEMENT IMPROVEMENTS OVER LLAC

Following optimization, a full set of results were obtained on all cycles, and these are summarized for NO_X, CO_2, and N_2O in Table 17 below. It should be noted that the RMC C1 results indicated potential for further refinement of the dosing calibration, although this was not completed until later in the program. These results were generally indicating numbers that were roughly 40-50% below the program targets at 0.04 g/kW-hr. At the same time, CO_2 levels were comparable to or slightly below the baseline engine. The N_2O levels were comparable to what was observed on the base engine, although there was a 20% increase in N_2O on the LLAC (which also had a nearly 50X reduction in tailpipe NO_X at the same time). It should be noted that all of these values, including the LLAC would be below the level that is currently regulated for on-road engines at 0.10 grams per brake horsepower hour (g/hp-hr), which would translate to 0.13 g/kW-hr.

TABLE 17. PACKAGE 1 RESULTS FOR OPEN CRANKCASE (OCV) CONFIGURATION WITH 12,000-HOUR DEVELOPMENT AGED PARTS

Cycle	EO NO_X, g/kW-hr	TP NO_X, g/kW-hr	CO_2, g/kW-hr	Baseline CO_2, g/kW-hr	TP N_2O, g/kW-hr
Cold NRTC	2.1	0.138	758	761	0.06
Hot NRTC	2.3	0.015	741	747	0.07
Composite NRTC	2.3	0.021	742	748	0.07
RMC	2.6	0.024	694	697	0.06
LLAC	3.9	0.035	835	836	0.12

Although these levels are well below the 0.04 g/kW-hr target, it was still important to examine the potential to maximize available margin below the program targets. The final more rigorous DAAAC aging planned for the final demonstrations would likely result in reductions in aftertreatment efficiency, and the potential impacts of DPF infrequent regeneration adjustment (IRAF) had not yet been applied. It should be noted that these results were generated with the crankcase gases connected to the tailpipe downstream of the AT system, as required in 40 CFR 1065 for engines which normally have an open crankcase ventilation system, as the 6.8L engine does.

3.5 Impact of Crankcase Emissions and Closed Crankcase Ventilation (CCV)

In working to further reduce tailpipe emissions on the hot NRTC cycle, it was observed the aftertreatment temperatures were essentially satisfactory over the entire cycle, and that further adjustments to dosing strategy did not result in further changes in tailpipe emission behavior. At this point SwRI conducted several additional investigations into both the system and the measurements. One of these included disconnecting the crankcase vent line from the tailpipe, to see of this affected the measurement significantly. This last change result in a substantial drop in measured NO_X levels. A comparison continuous tailpipe NO_X behavior of the system with and without the crankcase line hooked up to the tailpipe is shown below in Figure 72. As can be seen, following the very early tailpipe spike, there is a continuous but low level of NO_X accumulation occurring with the crankcase line plumbed to the tailpipe, and that is essentially gone after about 300 seconds into the cycle with the line disconnected. The difference between these two cycles was on the order of 0.01 g/kW-hr, which represents two-thirds of the total tailpipe NO_X shown in the Table 17 for the OCV configuration.

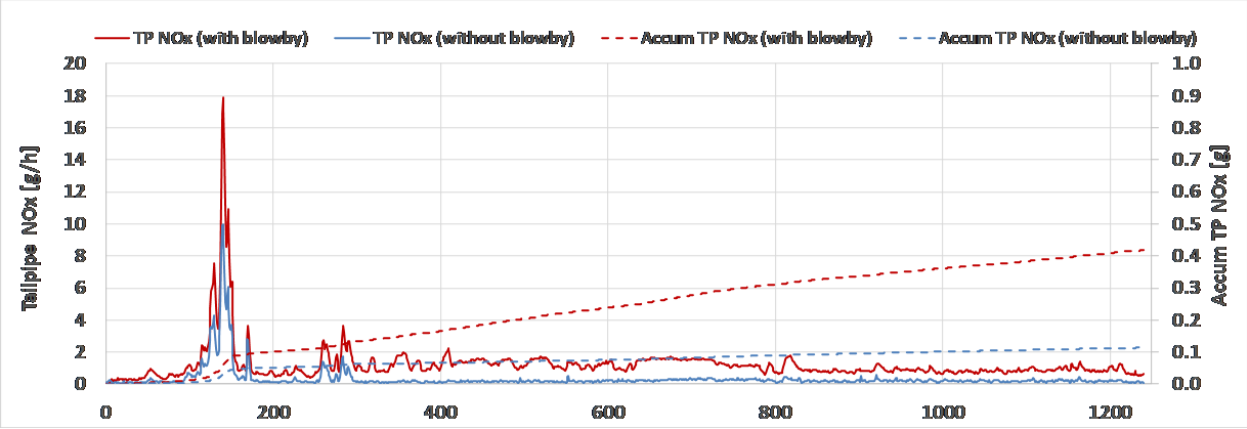


FIGURE 72. IMPACT OF CRANKCASE EMISSIONS OF DEERE 6068 ENGINE ON HOT-START NRTC EMISSIONS

To facilitate a better understanding of the crankcase emissions, additional measurement instrumentation was installed to directly monitor the crankcase gas flow rate and NO_X concentration. The results for direct crankcase gas measurements on the NRTC are shown below in Figure 73 for NO_X concentration, and Figure 74 for flow rate, respectively. The NO_X concentration in the blowby gases is generally between about 70 ppm and 120 ppm, and it can be seen to vary somewhat weakly with in-cylinder (engine-out) NO_X levels. Overall the crankcase NO_X concentration appears to be roughly 20-35% of the in-cylinder level. It should be noted that

this damped response makes sense given that the crankcase itself will serve as something of a mixing and dilution chamber for the gases that escape the combustion chamber past the piston rings. The crankcase gas flow rate, shown in Figure 74, demonstrates a very strong correlation to the exhaust flow rate, with the crankcase flow rate generally seen at about 1 percent of exhaust flow. This is a level that is consistent with other engines, though on the higher end of the typical range. The data from direct blowby measurements shown in these figures was used to determine a $BSNO_X$ rate, and that value was 0.011 g/kW-hr, consistent with the 0.01 g/kW-hr level predicted by the difference between the measured dilute levels with and without the crankcase line connected to the tailpipe.

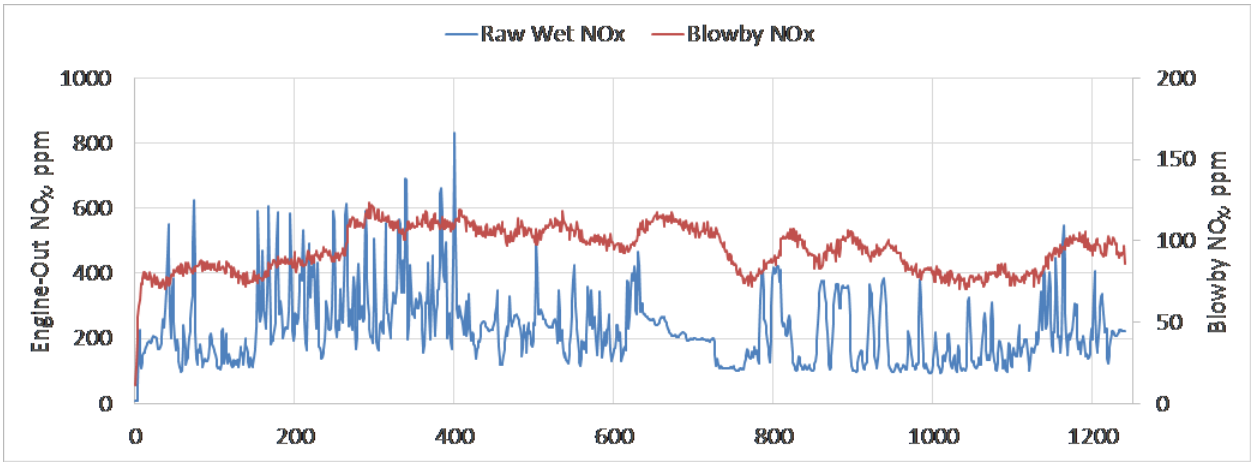


FIGURE 73. CRANKCASE GAS NO_X CONCENTRATION AS COMPARED TO ENGINE-OUT LEVEL ON NRTC

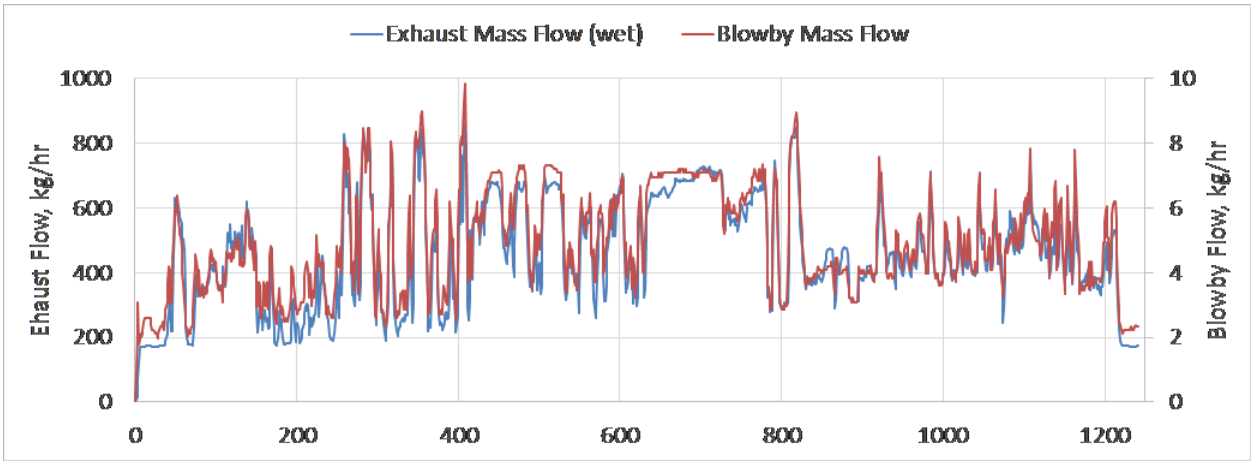


FIGURE 74. CRANKCASE GAS FLOW RATE AS COMPARED TO ENGINE EXHAUST FLOW ON NRTC

Similar results are shown for the RMC in Figure 75 for NO_X concentration and Figure 76 for crankcase flow rate, respectively. Here the measured tailpipe NO_X impact of the crankcase gases is 0.013 g/kW-hr, slightly higher given the higher load cycle. Given the steady-state nature of this cycle from an engine standpoint, the relationship between engine out NO_X and crankcase NO_X concentration is more apparent, but still somewhat damped. Blowby flow rate remains highly correlated to exhaust flow rate, with the blowby flow rate generally at about 1% of the exhaust flow.

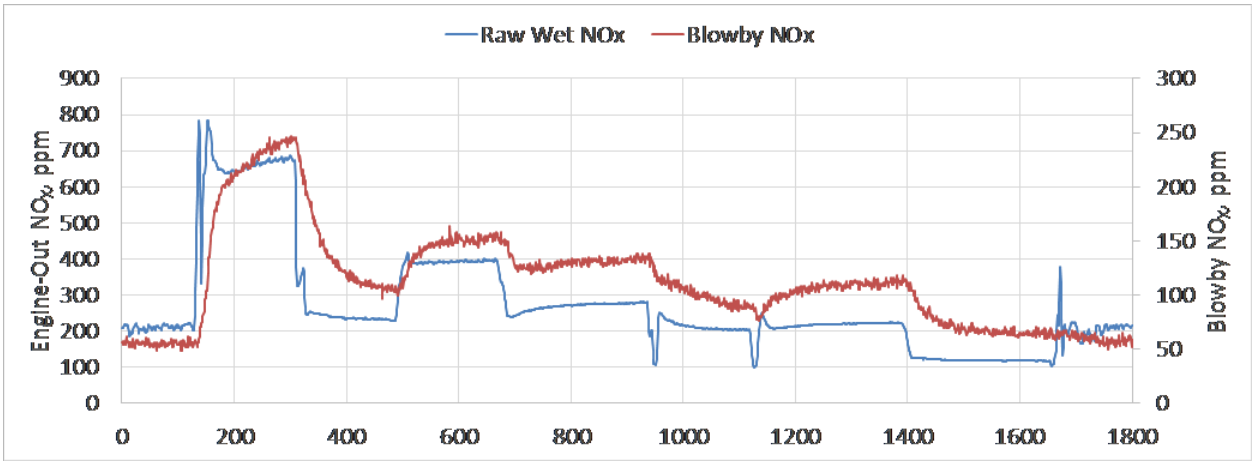


FIGURE 75. CRANKCASE GAS NOx CONCENTRATION AS COMPARED TO ENGINE-OUT LEVEL ON RMC

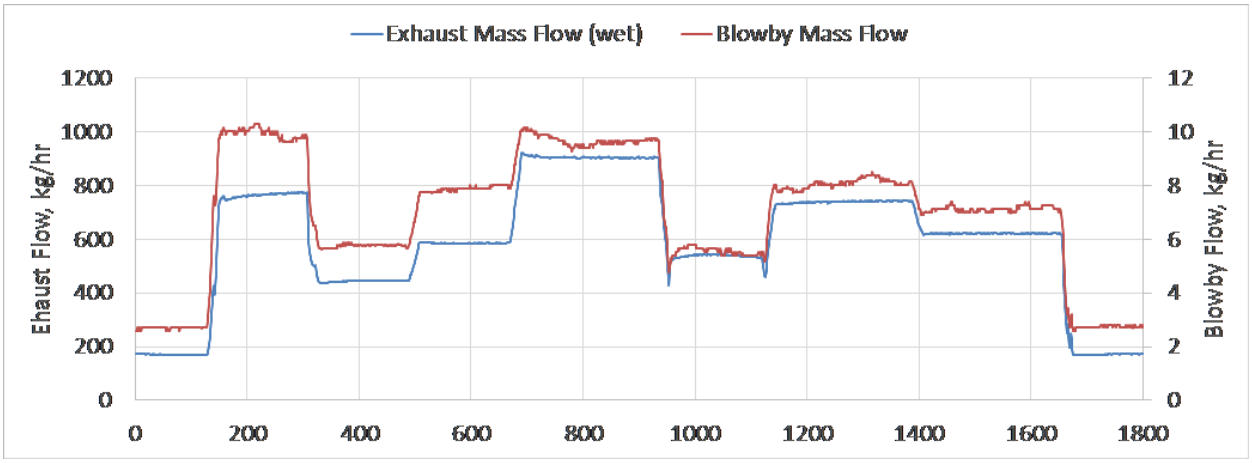


FIGURE 76. CRANKCASE GAS FLOW RATE AS COMPARED TO ENGINE EXHAUST FLOW ON RMC

As result of this initial experimentation, a full data set for all cycles was generated in a simulated closed crankcase ventilation (CCV) configuration, wherein the crankcase gases were not connected to the tailpipe. In addition, further improvements were made to the dosing calibration for the RMC and the LLAC. The resulting cycle results in the CCV configuration are given in Table 18. The resulting tailpipe NO_X levels are significantly lower for nearly all cycles, with the exception of the cold-start NRTC, which was similar to the OCV level. This makes sense for the cold-start given that the cold-start exhaust emissions are still an order of magnitude above what is observed for the crankcase emissions. However, this still results in an NRTC composite level with Development Aged parts at 0.011 g/kW-hr which is more than 70% below the program target. The RMC and LLAC cycles are similar 85% and 90% below program targets, respectively. This is a good start point for the Package 1 work, because there is still DAAAC aging and IRAF to account for, as well as production variability.

TABLE 18. FINAL PACKAGE 1 RESULTS FOR CLOSED CRANKCASE (CCV) CONFIGURATION WITH 12,000 HOUR DEVELOPMENT AGED PARTS

Cycle	EO NO_X, g/kW-hr	TP NO_X, g/kW-hr	NO_X Efficiency, %	CO_2, g/kW-hr	Baseline CO_2, g/kW-hr	TP N_2O, g/kW-hr
Cold NRTC	2.3	0.138	93.9	763	761	0.06
Hot NRTC	2.4	0.004	99.8	741	747	0.07
Composite NRTC	**2.4**	**0.011**	**99.5**	**745**	**748**	**0.07**
RMC	**2.6**	**0.006**	**99.7**	**690**	**697**	**0.05**
LLAC	**4.1**	**0.011**	**99.7**	**832**	**836**	**0.11**

3.6 Package 2 Results with Advanced Aftertreatment

Following these runs on Package 1, experiments were conducted on the Package 2 calibrations to examine the potential for a Conventional aftertreatment architecture to meet the Low NO_X targets while also achieving GHG reductions. Based on the CO_2 results outlined in Figure 65 earlier, and the relatively short time left before the reporting deadline, it was decided to focus on the CDA-enabled configurations for Package 2, because those showed CO_2 levels closest to meeting the desired targets. Additional approaches will be examined on the continuing work, but there was not sufficient time within this contract to evaluate all of those options with the advanced aftertreatment in place. The results are given below in Table 19

Cycle	EO NO_X, g/kW-hr	TP NO_X, g/kW-hr	NO_X Efficiency, %	CO_2, g/kW-hr	Baseline CO_2, g/kW-hr	CO_2 Improvement, %
Cold NRTC (CDA)	2.7	0.143	94.6	728	761	4.3%
Hot NRTC (CDA)	2.8	0.004	99.8	725	747	2.9%
Composite NRTC (CDA)	**2.8**	**0.011**	**99.6**	**725**	**748**	**3.0%**
RMC (CDA)	**3.7**	**0.020**	**99.7**	**671**	**697**	**3.7%**
LLAC (CDA)	**4.1**	**0.005**	**99.9**	**779**	**836**	**6.8%**

TABLE 19. PACKAGE 2 RESULTS WITH CDA AND CCV FOR 12,000-HOUR DEVELOPMENT AGED PARTS

Cycle	EO NO_X, g/kW-hr	TP NO_X, g/kW-hr	NO_X Efficiency, %	CO_2, g/kW-hr	Baseline CO_2, g/kW-hr	CO_2 Improvement, %
Cold NRTC (CDA)	2.7	0.143	94.6	728	761	4.3%
Hot NRTC (CDA)	2.8	0.004	99.8	725	747	2.9%
Composite NRTC (CDA)	**2.8**	**0.011**	**99.6**	**725**	**748**	**3.0%**
RMC (CDA)	**3.7**	**0.020**	**99.7**	**671**	**697**	**3.7%**
LLAC (CDA)	**4.1**	**0.005**	**99.9**	**779**	**836**	**6.8%**

These early runs with CDA indicated CO_2 improvements of between 3% and 7%, depending on the duty cycle, which is near to the program targets. In addition tailpipe NO_X emissions were below targets, although the amount varied by duty cycle. For the NRTC, the tailpipe NO_X was the same as Package 1, for the LLAC it was lower than Package 1, and for the RMC tailpipe NO_X was higher than Package 1. These changes have implications for the available compliance margins, although the most significant change was a lower margin for the RMC cycle.

Engine-out NO_X was generally higher with Package 2, as expected when looking for CO_2 reductions, although the amount again varied by duty cycle, with the largest NO_X increase being evident on the RMC. This early RMC result indicates that further efforts may be needed for high load NO_X control to maintain desired compliance margins.

A comparison of Tailpipe behavior on the RMC is given in Figure 77, while engine-out NO_X and SCR bed temperatures are shown in Figure 78. Even though more favorable SCR temperatures are observed under low load conditions with CDA, the higher engine-out NO_X rate for the Package 2 calibration still resulted in more NO_X breakthrough at the tailpipe for Package 2, although further optimization may reduce that somewhat.

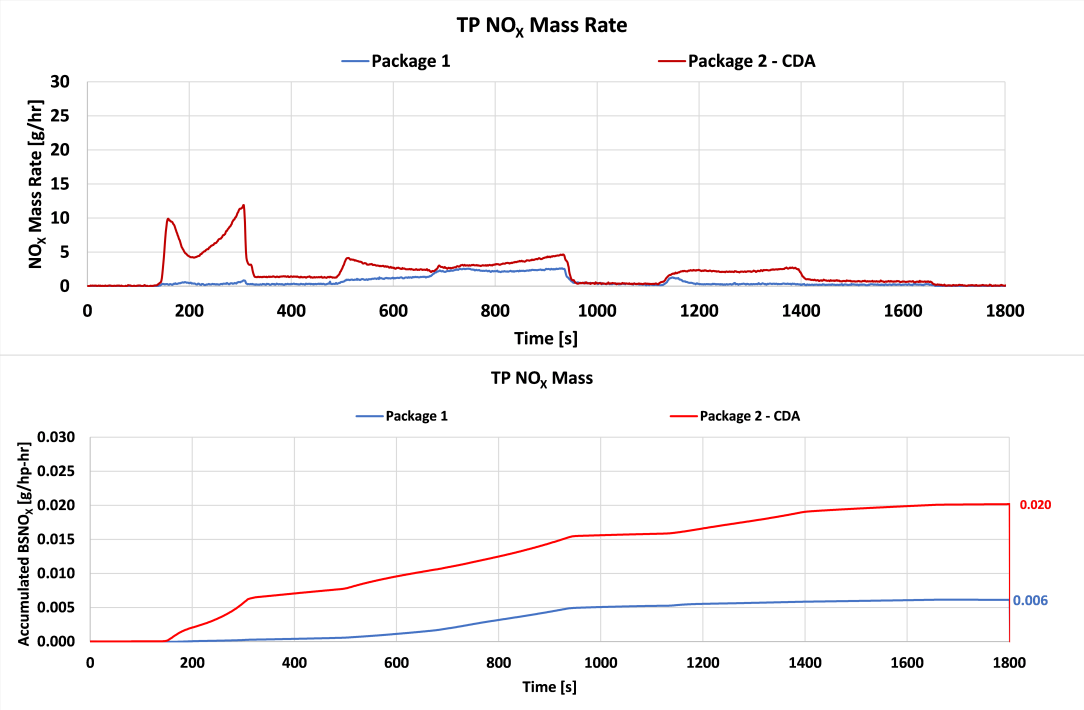


FIGURE 77. TAILPIPE NOX COMPARISON OF PACKAGE 2 WITH CDA VERSUS PACKAGE 1 ON RMC

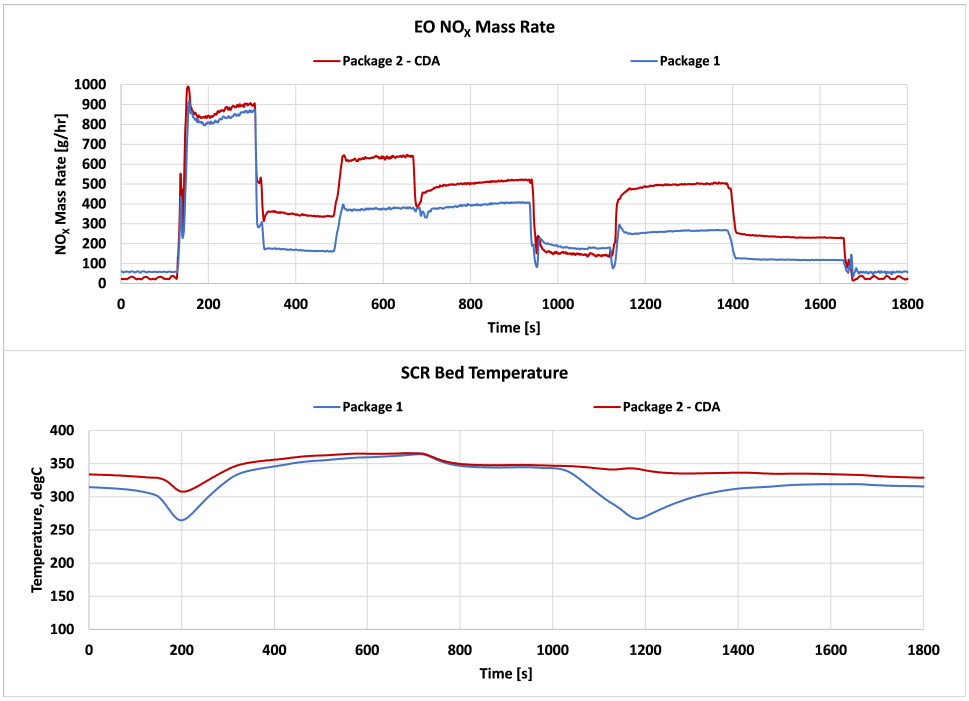


FIGURE 78. COMPARISON OF ENGINE-OUT NOX AND SCR TEMPERATURE – PACKAGE 2 WITH CDA VERSUS PACKAGE 1 ON RMC

A comparison of DEF dosing behavior between Package 2 and Package 1 is shown in Figure 79, and a comparison of ammonia storage behavior is given in Figure 80. These comparisons show slightly higher ammonia-to-NO_X ratio (ANR) for Package 2 in some areas, but it should be noted that there is less storage in some sections because of the higher temperatures on Package 2, which is due in part to CDA. It should be noted that in some areas the ANR is near 1 or in some cases even less than 1, and in the case of Package 2 there is less storage available. This behavior does indicate that RMC NO_X with CDA in Package 2 can likely be further reduced with a further improved calibration of the dosing.

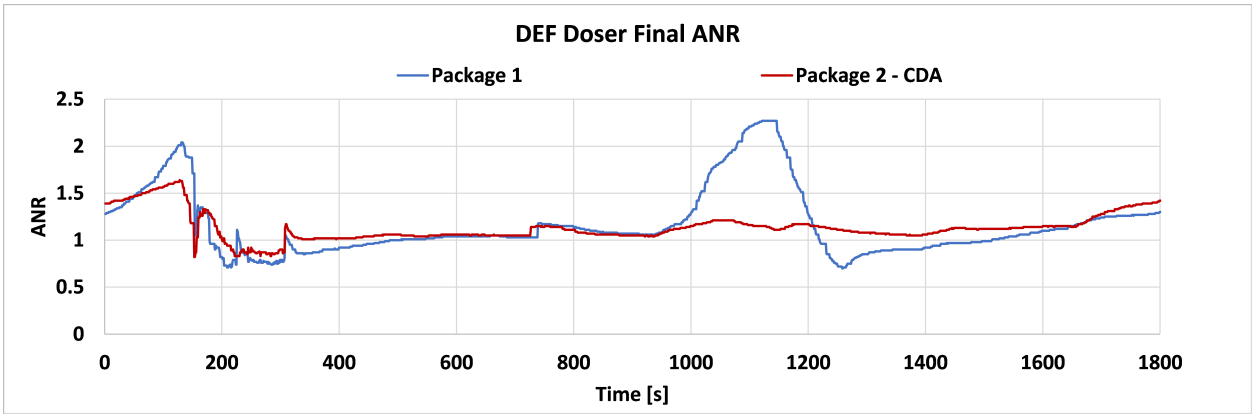


FIGURE 79. DOSING BEHAVIOR COMPARISON OF PACKAGE 2 WITH CDA VERSUS PACKAGE 1 ON RMC

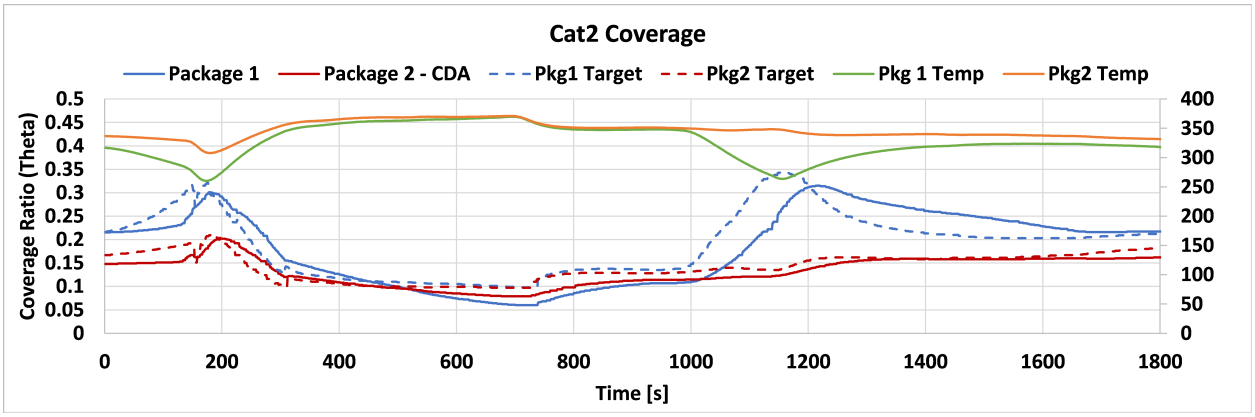


FIGURE 80. SCR AMMONIA STORAGE AND TEMPERATURE BEHAVIOR COMPARISON OF PACKAGE 2 WITH CDA VERSUS PACKAGE 1 ON RMC

Figure 81 shows a comparison of tailpipe NO_X behavior over the LLAC for Package 2 and Package 1, while Figure 82 shows a comparison of temperature behaviors over the LLAC. Engine-out NO_X was essentially the same for both packages over the LLAC, but temperatures were more favorable with the Package 2 configuration due to the impact of CDA at light load in maintaining higher exhaust temperatures. As a result the NO_X performance over the LLAC was improved over the already very good Package 1 performance. This indicates that there is likely room to adjust engine-out NO_X for further CO_2 improvement, although on the LLAC the current level is well within the target range.

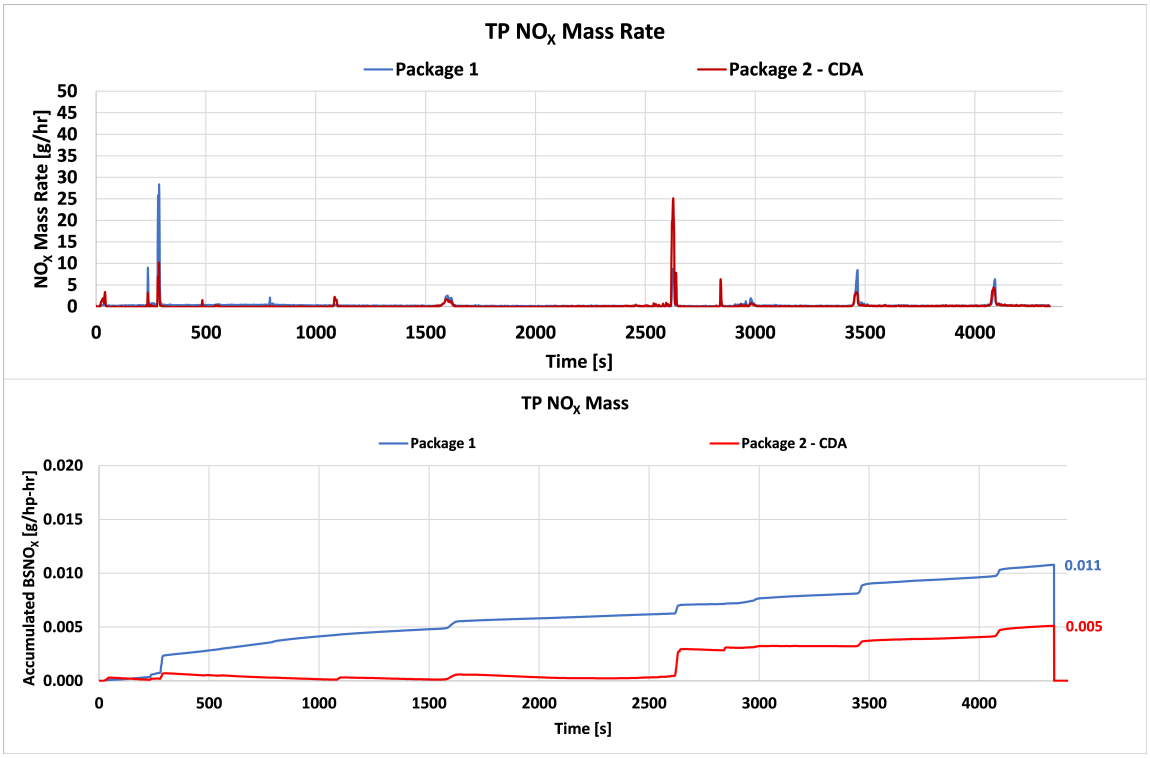


FIGURE 81. TAILPIPE NO_X COMPARISON OF PACKAGE 2 WITH CDA VERSUS PACKAGE 1 ON LLAC

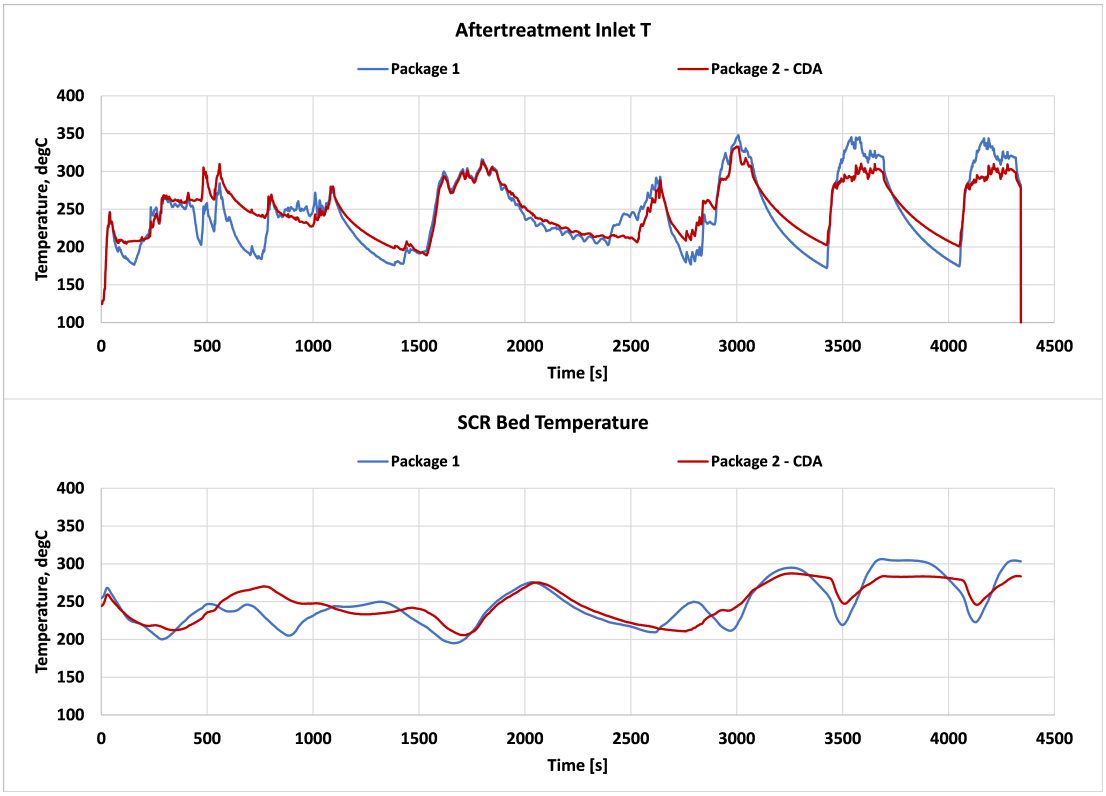


FIGURE 82. TEMPERATURE COMPARISON OF PACKAGE 2 WITH CDA VERSUS PACKAGE 1 ON LLAC

Package 2 testing was also run using the DSF algorithm to enhance the performance of the CDA system. The results of these tests are given in Table 20. Tailpipe NO_X performance was similar to that observed for Package 1, but CO_2 was improved between about 4% to 8%, very close to the target range. It should be noted that due to time constraints and an instrumentation malfunction, a results was not obtained for the RMC. However, based on previous experiments the performance is expected to be similar on this cycle between CDA and DSF. For the NRTC and the LLAC, the use of DSF improved CO_2 an additional 1% over what was observed using CDA alone, while maintaining or even improving NO_X margins slightly.

TABLE 20. PACKAGE 2 RESULTS WITH DSF AND CCV FOR 12,000-HOUR DEVELOPMENT AGED PARTS

Cycle	EO NO_X, g/kW-hr	TP NO_X, g/kW-hr	NO_X Efficiency, %	CO_2, g/kW-hr	Baseline CO_2, g/kW-hr	CO_2 Improvement, %
Cold NRTC (DSF)	2.8	0.150	94.6	728	761	4.3%
Hot NRTC (DSF)	3.0	0.003	99.9	720	747	3.6%
Composite NRTC (DSF)	**3.0**	**0.010**	**99.6**	**720**	**748**	**3.7%**
RMC (DSF)	**n/a at time of report but expected to be similar to CDA**					
LLAC (DSF)	**4.4**	**0.014**	**99.7**	**772**	**836**	**7.7%**

A comparison of cylinder behavior between the base CDA and DSF controls for cylinder deactivation can be seen between Figure 83 for the CDA and Figure 84 for the DSF, respectively. With the DSF controls, it was possible to run a much larger portion of the cycle with deactivated

cylinders at light loads, resulting in a larger CO_2 benefit, while still maintaining very good aftertreatment performance .

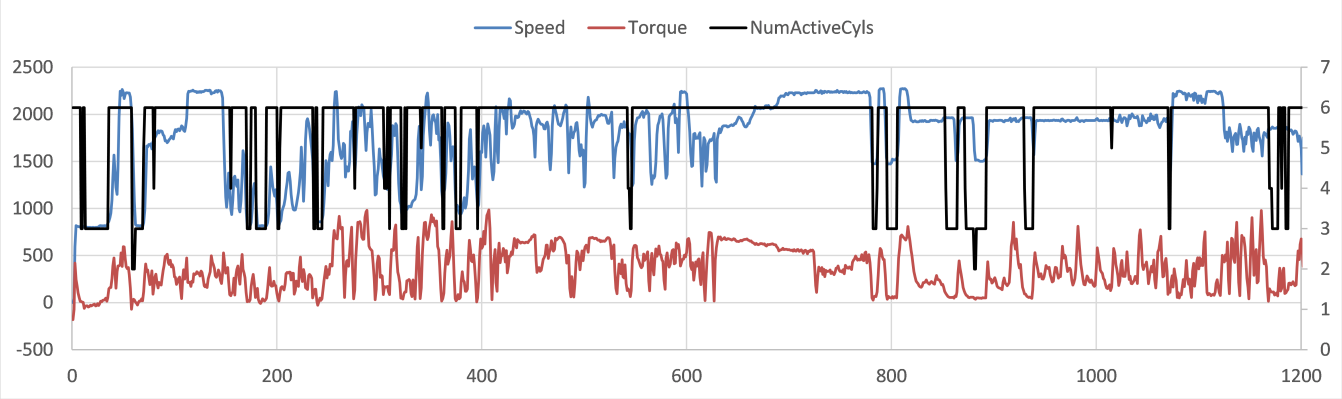


FIGURE 83. CYLINDER DEACTIVATION BEHAVIOR OVER HOT NRTC WITH BASE CDA CONTROLS

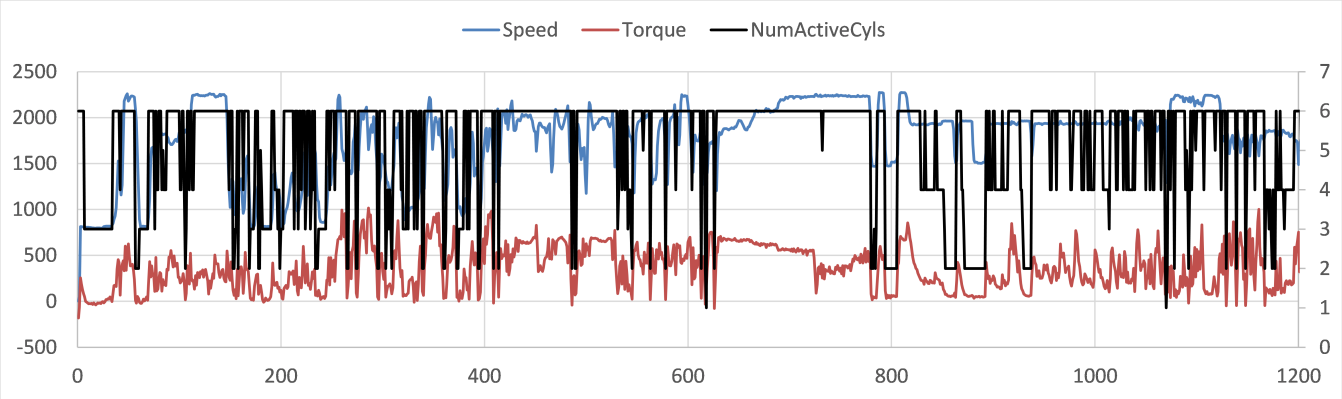


FIGURE 84. CYLINDER DEACTIVATION BEHAVIOR OVER HOT NRTC WITH DSF CONTROLS

3.7 Impact of Infrequent Regeneration Adjustment Factor (IRAF)

A key aspect of compliance measurements is the need to account for the impact of infrequent regeneration events, such as DPF regeneration, on tailpipe emissions. This is required under 40 CFR 1065.680. Although these adjustments are relatively small compared to most current Tier 4 certification levels, they could be quite significant at Low NO_X levels. Therefore, it is important that the system design must maintain good NO_X conversion during regeneration events, otherwise high regeneration emissions could have a serious negative impact on compliance margins. As part of a complete technology demonstration, an assessment of the IRAF is needed.

Because the development of a transient regeneration controller is not part of the scope of the demonstration program, it is not possible to directly measure emissions during regeneration on transient cycles. Instead, the following approach is used to make measurements that will allow projection of the IRAF. Because regeneration does not normally occur during the demonstration

emissions tests, it is necessary to calculate an Upward Adjustment Factor (UAF), which is described in 40 CFR 1065.680(1) as follows:

$$UAF_{[cycle]} = EF_{A[cycle]} - EF_{L[cycle]}$$

Eq. 1065.680-1

Where:

$EF_{A[cycle]}$ = the average emission factor over the test segment as determined in paragraph (a)(4) of this section.

$EF_{L[cycle]}$ = measured emissions over a complete test segment in which active regeneration does not occur.

From 40 CFR 1065.680(a)(4) at noted above:

$$EF_{A[cycle]} = F_{[cycle]} \cdot EF_{H[cycle]} + (1.00 - F_{[cycle]}) \cdot EF_{L[cycle]}$$

Eq. 1065.680-3

Where:

$F_{[cycle]}$ = the frequency of the regeneration event during the test segment, expressed in terms of the fraction of equivalent test segments during which active regeneration occurs, as described in paragraph (a)(5) of this section.

In order to make this calculation four key parameters must be known:

1. Engine-out emissions during a regeneration event
2. Aftertreatment NO_X conversion capability under regeneration conditions
3. The duration of a regeneration event
4. The period between individual regeneration events

The methodology used to generate each of these parameters is described below. For the Deere 6.8L demo engine, engine out emissions during regeneration were initially projected based on assessing emissions of the baseline engine with the stock AT system during regeneration. A conservative estimate would then utilize the same engine-out emissions, unless it is found that these are too high to support a reasonable UAF. In that case, a projection is made of what engine-out NO_X levels would need to be lowered to support a workable UAF, and a discussion is included regarding whether such a level is feasible. Generally, regeneration modes often involve operation with either low EGR rates, or no EGR at all. For the NRTC, the engine-out NO_X emission level was 5 g/kW-hr, considerably higher than the normal baseline level of 2.6 g/kW-hr. This helps to ensure sufficient oxygen is always available to deal with the additional post-injected fuel required during regeneration without generating excess soot or causing any issues with long-term DOC fouling.

To determine the NO_X conversion capability of the advanced AT system, a series of experiments were run at different DPF regeneration temperature targets and different exhaust flow rates. NO_X conversion over zeolite SCR catalysts is generally more difficult at the elevated temperatures seen during regeneration due to parasitic ammonia oxidation, especially in the case of copper-based zeolite SCR catalysts. Therefore, excess ammonia must be injected to sustain high NO_X conversion, in the form of ANR significantly above 1. The results of these experiments are given below in Figure 85 at low-to-mid space velocity, and in Figure 86 at higher space velocity. Regeneration temperatures at the DPF outlet of 570°C, 585°C, and 600°C were

examined. Temperatures below 570°C are not practical because the SCR catalyst downstream of the DPF must reach at least 550°C to ensure good long term $deSO_X$. At the same time, temperatures above 600°C are not necessary for either $deSO_X$ or soot oxidation, and would likely result in more rapid thermal degradation of the SCR catalysts. In the Stage 3 on-road work, a regeneration temperature of 600°C was used, but that system also had a LO-SCR to assist in NO_X control under regeneration conditions, and featured HC injection after the LO-SCR. This allowed the LO-SCR which was at lower temperatures during regeneration to handle the bulk of NO_X control under those conditions. However, in a single SCR configuration like the one being examined in this program, this is not the case, therefore it is imperative that the SCR can achieve good NO_X conversion at regeneration temperatures.

It can be seen from the figures that high NO_X conversion rates, in excess of 90% can be reached on the Development Aged Team 2 system at only ANR of 4 and higher at temperatures of 570°C. ANR above 4.5 at lower space velocity, and above 4 at higher space velocity is not practical due to limitations of maximum DEF doser flow rate, and limits of how much DEF could be properly mixed and distributed. It should be noted that NO_X conversion was generally better at higher space velocity conditions, due to the fact the parasitic ammonia oxidation rates were lower at those higher exhaust flow rates. At 570°C, these data were used to project a NO_X conversion capability of 93% under regeneration conditions. At 585°C, the projected NO_X conversion capability was only 75%.

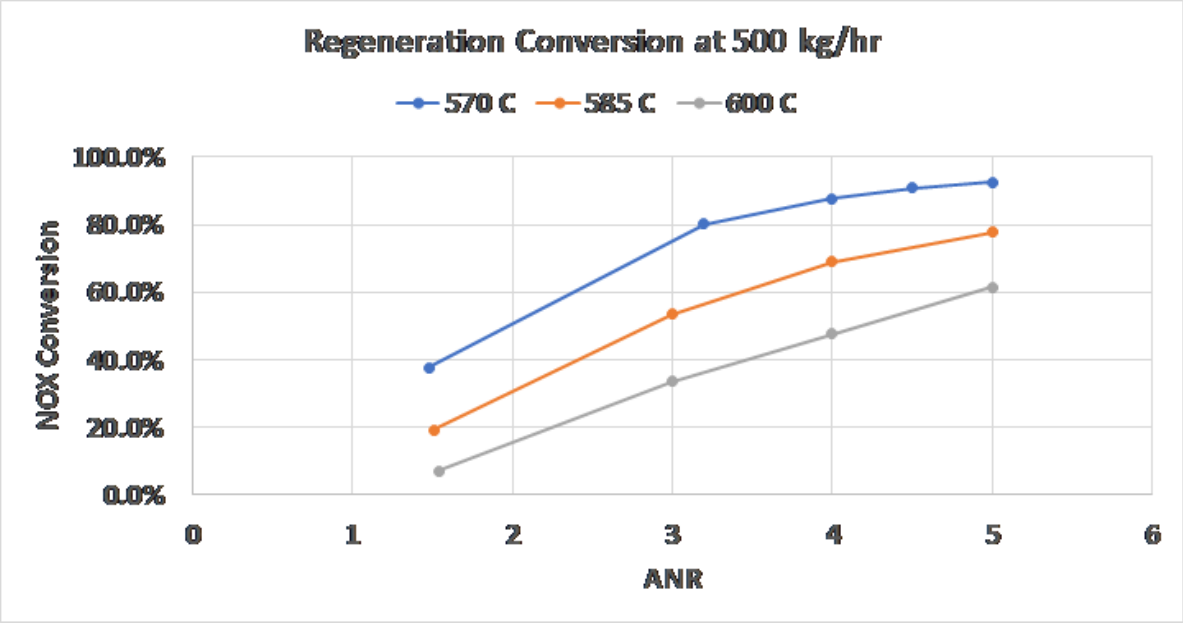


FIGURE 85. TEAM 2 NO_X CONVERSION UNDER DPF REGENERATION CONDITIONS AT 22.5K HR^{-1} SPACE VELOCITY

The regeneration duration for the baseline engine was 40 minutes, and the period between regenerations for the baseline engine was every 80 hours. This results in a regeneration frequency of 0.8%. This duration is generally driven by the need for periodic $deSO_X$ of the SCR catalyst. Assessment of the soot loading the pressure drop behavior for the Low NO_X system during the three test cycles was made in comparison to the baseline. It was determined that the Low NOX system would not result in increased engine-out PM and soot loading rates, therefore the baseline

characteristics were utilized for the projections. In the case of the NRTC, a slight increase in pressure drop was not observed across multiple repeat cycles, therefore a slightly shorter regeneration period of 68 hours (200 NRTC cycles) was used. For the RMC cycle, good passive soot oxidation is always observed, and the DPF generally keeps itself clean on that cycle. As a result the base period of 80 hours was used for the RMC cycle. In the case of the LLAC, temperatures are mostly below those required for good passive soot oxidation, therefore a much shorter period of 28 hours (23 LLAC cycles) was utilized for the calculations.

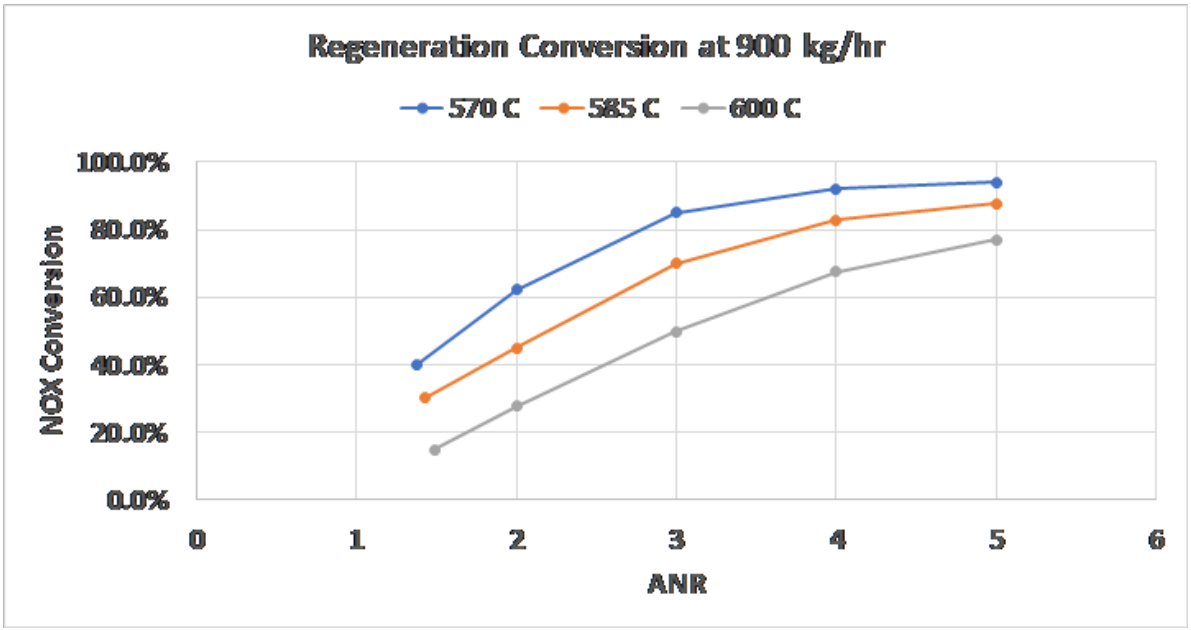


FIGURE 86. TEAM 2 NO_X CONVERSION UNDER DPF REGENERATION CONDITIONS AT 40K HR^{-1} SPACE VELOCITY

Using all these parameters noted above, a projection of the UAF was made using a 570°C target regeneration temperature. Those calculations are summarized below in Figure 87 for the NRTC. The resulting UAF is 0.004 g/kW-hr. A similar projected was made at a 585°C target regeneration temperature, and this calculation is shown in Figure 88.

	cycles	hours	tp bsnox	wtd mass		
NRTC	200	68.61	0.011	0.754722	grams	
Regen NRTC	2	0.69	0.350	0.240139	grams	
next NRTC	1	0.34	0.175	0.060035	grams	
total	203	69.6		1.054896	grams	
				0.01515	g/kw-hr	
	EFL	0.011	g/kw-hr	*0.0041*	*g/kw-hr*	
	EFH	0.292	g/kw-hr			
freq (F)	0.014778	0.014778	uaf	0.004		

FIGURE 87. IRAF CALCULATIONS FOR TEAM 2 SYSTEM ON NRTC CYCLE AT 570°C TARGET TEMPERATURE

Note that at 585°C it was necessary to project that engine-out NO_X levels would stay at 2.4 g/kW-hr during regeneration, which would require the use of EGR during DPF regeneration modes. While this can be done, it is not ideal, and could result in some difficulties maintaining sufficient oxygen availability for good exotherms during transients. However, even with this lower engine-out NO_X level, the much lower NO_X conversion capability of only 75% means that the regeneration cycle emissions are much higher, resulting in a UAF of 0.007 g/kW-hr. This was deemed to be an unsustainable high UAF at a NO_X standard of 0.04 g/kW-hr, as regeneration emissions alone would actually be higher to all other NRTC emissions, which is problematic for compliance margins. As a result the 570°C temperature was chosen, and this is the temperature that will be used during the final DAAAC aging protocol in the follow-on program under 20MSC005. Projections were also made for the RMC and LLAC cycles using the 570°C target temperature.

	cycles	hours	tp bsnox	wtd mass		
NRTC	200	68.61	0.011	0.754722	grams	
Regen NRT	2	0.69	0.600	0.411667	grams	
next NRTC	1	0.34	0.300	0.102917	grams	
total	203	69.6		1.269306	grams	
				0.01823	g/kw-hr	
	EFL	0.011	g/kw-hr	*0.0072*	*g/kw-hr*	
	EFH	0.500	g/kw-hr			
freq (F)	0.014778	0.014778	uaf	0.007		

FIGURE 88. IRAF CALCULATIONS FOR TEAM 2 SYSTEM ON NRTC CYCLE AT 585°C TARGET TEMPERATURE

	cycles	hours	tp bsnox	wtd mass		
RMC	160	80	0.006	0.48	grams	
regen rmc	2	1.00	0.323	0.323167	grams	
total	162	81		0.803167	grams	
				0.009916	g/hp-hr	
	EFL	0.0060	g/hp-hr	0.0039	*g/hp-hr*	
	EFH	0.3232	g/hp-hr			
freq (F)	0.012346	0.012346	uaf	0.004		

FIGURE 89. IRAF CALCULATIONS FOR TEAM 2 SYSTEM ON RMC CYCLE

	cycles	hours	tp bsnox	wtd mass		
LLAC	23	27.70861	0.047	1.302305	grams	
regen LLAC	1	1.204722	0.209	0.252054	grams	
total	24	28.91333		1.554359	grams	
				0.053759	g/hp-hr	
	EFL	0.0470	g/hp-hr	*0.0068*	*g/hp-hr*	
	EFH	0.2092	g/hp-hr			
freq	0.041667	0.042	uaf	0.007		

FIGURE 90. IRAF CALCULATIONS FOR TEAM 2 SYSTEM ON LLAC CYCLE

As noted earlier, a DPF outlet temperature should produce SCR temperatures at or above 550°C on the SCR, which should be sufficient for long-term deSO_X. However, if during the early stages of the DAAAC durability, it is found that this target temperature is not sufficient to adequately control long-term sulfation of the SCR, then a slightly higher target temperature would need to be used, which would result in the need to re-assess these IRAF calculations.

3.8 Discussion of NO_X Emission Results and Projected Compliance Margins

An important component of the determination of technology feasibility is the discussion of compliance margins. For a technology demonstration program such as this one, by necessity only a single example of hardware will be evaluated. However, in production a compliant system must be produced many thousands of times, and this implies that there will be some level of variation in the production components. There will also be measurement variation, and other environmental factors which can lead to increased variability. Therefore, it is necessary in production for the system as a whole to have a target level be below the standard by a certain amount, to leave enough room for these factors, such that emissions will still be compliant if a bad combination of these variations stacks up on a given engine. The necessary compliance margin can be challenging to determine because it is not always clear how much variation there will be in a future production

operating at lower emission levels than current systems. Some information from current systems can be useful, but this has to be applied with care because current systems may vary more in certain areas because manufacturers do not have to spend resources to reduce variability more than is necessary to meet current, less restrictive regulatory targets.

The discussion below attempts to apply the data generated in this program, along with lessons learned from previous programs and stakeholder discussions, to project the compliance margins available for the demonstrated systems. It will be up to stakeholders to make their own judgements regarding what an adequate compliance margin is in the context individual levels of risk tolerance, although SwRI can make some recommendations in this area.

In the context of this discussion, compliance margin will be defined as the difference between the FUL emission level, after durability and the addition of any UAF for regeneration, and a projected emission standard. The methodology is illustrated below in Figure 91. The scenario shown is one of the original cases used for the development of emission targets that were given to the aftertreatment suppliers for simulation work in the development of Low NO_X AT systems used in this program. In the case below, the final compliance margins were 25%, indicated that the final projected numbers were 25% below the emission standard used for the calculation. Margins are also shown in engineering units of g/kW-hr. It should be noted that the LLC "standard" shown does not reflect a particular program target, it is only an example for calculation purposes.

In this projection, engine-out emissions and the projected standards are initial system inputs. The performance of the de-greened AT system is given as a "Conversion" percentage, and an FUL durability loss margin is entered as the projected loss in conversion due to durability (this would be the projected impact of any final deterioration factor). Those numbers are then used to calculation a "FUL Tailpipe" value which is the end-of-life emission level projection. The IRAF is then added to this level to produce the final TP Composite, which is the compliance value that is compared to the standard. The Margin is then the calculated difference between that final composite level of the standard, shown both as a percentage and an absolute difference. It should be noted that this calculation can be run forward to project a compliance margin based on these inputs, or backwards to project an engine's required certification design target, starting with a desired margin and assumed durability loss of performance.

For the example shown below in Figure 91, the Engine-Out emission level is the Deere 6.8L engine baseline testing. The FUL durability loss margins here are taken from the values demonstrated in the Stage 3 on-road demonstration program using the rigorous DAAAC protocol (accounting for thermal aging, oil poisoning and sulfur poisoning), and the projections were scaled to an 8,000-hour full useful life. The IRAF numbers were also taken from the Stage 3 on-road program. Scenarios were run at varying levels of de-greened AT system performance, and the values shown gave design targets that produced a compliance margin of about 25 percent. The certification conversion targets were then used as part of system design, and they were also used as initial performance targets for evaluation of the systems.

		NRTC 5% Cold g/kw-hr	NRTC 95% Hot g/kw-hr	RMC g/kw-hr	LLC g/kw-hr
	Standard	**0.04**		**0.04**	**0.12**
Certification Targets	Engine-Out	3.1	3.1	3.1	5.0
	Conversion	**96.5%**	**99.7%**	**99.6%**	**99.3%**
	Tailpipe	**0.109**	**0.010**	**0.012**	**0.035**
	TP Composite		**0.015**		
	EO Composite		**3.1**		
	Composite Conversion		**99.5%**		
FUL Compliance	FUL Durability Loss Margin	**0.80%**	**0.40%**	**0.50%**	**1.00%**
	FUL Conversion	**95.7%**	**99.3%**	**99.1%**	**98.3%**
	FUL Tailpipe	0.133	0.023	0.028	0.085
	FUL Composite Conversion		**99.1%**		
	IRAF		0.002	0.002	0.004
	Final TP Composite		**0.031**	**0.030**	**0.089**
	Margin to Standard		24%	24%	26%
			0.009	**0.010**	**0.031**

FIGURE 91. COMPLIANCE MARGIN CALCULATION EXAMPLE USING PACKAGE 1 PROJECTIONS – 25% MARGIN SCENARIO

A similar calculation is shown in Figure 92, but this time for what would be considered a more conservative High Margin scenario. This calculation was targeted at a nominal 50% compliance margin to the same standards shown above in Figure 91. A look at the numbers indicates several changes that would likely be needed to reach that higher margin. These changes include some reduction in cold-start engine-out emissions, improvements to durability, and significant more aggressive certification conversion targets (such is 98.5% cold-start NO_X conversion up from 96.5%), which implies more technology is needed to meet these targets.

		NRTC 5% Cold g/kw-hr	NRTC 95% Hot g/kw-hr	RMC g/kw-hr	LLC g/kw-hr
	Standard	**0.04**		**0.04**	**0.12**
Certification Targets	Engine-Out	2.8	3.1	3.1	5.0
	Conversion	**98.5%**	**99.8%**	**99.8%**	**99.7%**
	Tailpipe	**0.042**	**0.006**	**0.006**	**0.015**
	TP Composite		**0.008**		
	EO Composite		**3.1**		
	Composite Conversion		**99.7%**		
FUL Compliance	FUL Durability Loss Margin	**0.60%**	**0.40%**	**0.40%**	**0.80%**
	FUL Conversion	**97.9%**	**99.4%**	**99.4%**	**98.9%**
	FUL Tailpipe	0.058	0.018	0.019	0.055
	FUL Composite Conversion		**99.3%**		
	IRAF		0.002	0.002	0.005
	Final TP Composite		**0.022**	**0.021**	**0.060**
	Margin to Standard		44%	49%	50%
			0.018	**0.019**	**0.060**

FIGURE 92. COMPLIANCE MARGIN CALCULATION EXAMPLE USING PACKAGE 1 PROJECTIONS – HIGH MARGIN SCENARIO

Using these methods, it is possible to take the performance levels observed earlier and project what the compliance margins might look like for these technology packages. In these projections, the actual measured emission results and IRAF adjustments shown earlier in the Results section will be used. It should be noted that the calculations shown below will still use assumed FUL durability loss margins. However, in the following program, a real FUL durability measurement will be made using the DAAAC protocol on the final system configuration. It should also be noted that given the emission levels that were seen, the LLC standard target used for these scenarios was revised downwards to 0.10 g/kW-hr, which represents a 2.5X multiplier over the NRTC target, similar to what was seen in the final adopted standards.

Margin projections for the Team 2 Package 1 system using a 12,000-hour FUL scenario are given below in Figure 93. The actual measured emission numbers from the final calibration for engine-out and tailpipe numbers are used, although it should be noted that the Development Aged tailpipe results are input here, which means that this is a conservative projection of available margin. The FUL durability loss margin values are based on the 600,000-mile results for the Stage 3RW on-road system (13,790 hours), which are close to 12,000 hours here. The IRAF numbers used in this projection are now the actual numbers based on measurements discussed earlier in this report. It should be noted that the Tailpipe numbers used here are for the Close Crankcase (CCV) configuration. The calculations below indicated a projected compliance margin (after durability and IRAF are accounted for) of 32%, 43%, and 41% for the NRTC, RMC, and LLC (as represented by the LLAC results), respectively. This is significantly better than the 25% margin discussed above, and on some cycles begins to approach the High Margin scenario.

		NRTC			
		5%	95%		
		Cold	Hot	RMC	LLC
		g/kw-hr	g/kw-hr	g/kw-hr	g/kw-hr
	Standard	0.04		0.04	0.10
Certification Targets	Engine-Out	2.3	2.4	2.6	4.1
	Conversion	94.0%	99.8%	99.8%	99.7%
	Tailpipe	0.138	0.004	0.006	0.011
	TP Composite		0.011		
	EO Composite		2.4		
	Composite Conversion		99.6%		
FUL Compliance	FUL Durability Loss Margin	0.7%	0.5%	0.5%	1.0%
	FUL Conversion	93.3%	99.3%	99.3%	98.7%
	FUL Tailpipe	0.155	0.016	0.019	0.052
	FUL Composite Conversion		99.0%		
	IRAF		0.004	0.004	0.007
	Final TP Composite		0.027	0.023	0.059
	Margin to Standard		32%	43%	41%
			0.013	0.017	0.041

FIGURE 93. COMPLIANCE MARGIN CALCULATIONS FOR TEAM 2 PACKAGE 1 SYSTEM FOR 12,000 HOUR FUL

This same projection with the same system was repeated for an 8,000-hours scenario, in the event that the decision is made not to extend FUL beyond the current level. For this case, the FUL durability loss margin is set equal to what was observed for the Stage 3RW on-road program at 435,000 miles, which is 10,000 hours compared to 8,000 hours here so still a somewhat conservative choice. The resulting calculation is given below in Figure 94.

		NRTC			
		5%	95%		
		Cold	Hot	RMC	LLC
		g/kw-hr	g/kw-hr	g/kw-hr	g/kw-hr
	Standard	0.04		0.04	0.10
Certification Targets	Engine-Out	2.3	2.4	2.6	4.1
	Conversion	94.0%	99.8%	99.8%	99.7%
	Tailpipe	0.138	0.004	0.006	0.011
	TP Composite		0.011		
	EO Composite		2.4		
	Composite Conversion		99.6%		
FUL Compliance	FUL Durability Loss Margin	0.4%	0.3%	0.3%	0.7%
	FUL Conversion	93.6%	99.5%	99.5%	99.0%
	FUL Tailpipe	0.148	0.011	0.014	0.040
	FUL Composite Conversion		99.2%		
	IRAF		0.004	0.004	0.007
	Final TP Composite		0.022	0.018	0.047
	Margin to Standard		45%	56%	53%
			0.018	0.022	0.053

FIGURE 94. COMPLIANCE MARGIN CALCULATIONS FOR TEAM 2 PACKAGE 1 SYSTEM FOR 8,000 HOUR FUL

Again it should be noted that this 8,000-hour scenario assumes the CCV configuration, and the calculation use the updated IRAF factors. Based on these calculations, the projected margins are 45%, 56%, and 53% for the NRTC, RMC, and LLC, respectively. The margin levels would essentially meet that 50% margin target for the High Margin scenario. It remains to be seen if the system can match the degradation levels on the DAAAC protocol observed in the Stage 3 on-road program, and there is an assumption of no degradation in the IRAF values. On the other hand, considering that the numbers used in Figure 94 for the Certification Tailpipe values are actually for Development Aged (hydrothermally to FUL) parts rather than actually de-greened parts, this makes the conclusion that the projection would meet the High Margin scenario a reasonable one.

A similar calculation is shown below for the 8,000 scenario, but this time using the Open Crankcase (OCV) numbers. It should be noted that the values used represent a reasonable level calibration improvement on the RMC and LLC from the values shown in Table 17, based on what was seen with calibration on the CCV system and the observed magnitude of the closed-crankcase emission impact. From these values in can be observed that with open crankcase the system margins are considerably smaller, not quite meeting the minimum margin on the NRTC in fact. This indicates that if the OCV configuration were to be retained, other technologies would be needed to make up the performance gap to achieve good compliance margins. Given that the CCV system was worth 0.01 g/kW-hr on the hot NRTC, there is not much room for improvement from other approaches. Therefore, it is likely that adoption of CCV would be an important choice to meet emission standards at these levels. As noted, this implies improved filtration and diagnostics.

		NRTC			
		5%	95%		
		Cold	Hot	RMC	LLC
		g/kw-hr	g/kw-hr	g/kw-hr	g/kw-hr
	Standard	0.04		0.04	0.10
Certification Targets	Engine-Out	2.3	2.4	2.6	4.1
	Conversion	94.0%	99.4%	99.3%	99.4%
	Tailpipe	0.138	0.015	0.018	0.025
	TP Composite		0.021		
	EO Composite		2.4		
	Composite Conversion		99.1%		
FUL Compliance	FUL Durability Loss Margin	0.4%	0.3%	0.3%	0.7%
	FUL Conversion	93.6%	99.1%	99.0%	98.7%
	FUL Tailpipe	0.148	0.022	0.026	0.053
	FUL Composite Conversion		98.8%		
	IRAF		0.004	0.004	0.007
	Final TP Composite		0.033	0.030	0.060
	Margin to Standard		18%	25%	40%
			0.007	0.010	0.040

FIGURE 95. COMPLIANCE MARGIN CALCULATIONS FOR TEAM 2 PACKAGE 1 WITH OPEN CRANKCASE (OCV) SYSTEM FOR 8,000 HOUR FUL

The same calculations can be used for Package 2, and a scenario is given below using the Package 2 test results which incorporate the CDA hardware and dynamic skip-fire (DSF) algorithm. Scenarios are again shown in the CCV configuration in for both 12,000-hour and 8000-hour scenarios in Figure 96 and Figure 97, respectively.

		NRTC			
		5%	95%		
		Cold	Hot	RMC	LLC
		g/kw-hr	g/kw-hr	g/kw-hr	g/kw-hr
	Standard	0.04		0.04	0.10
Certification Targets	Engine-Out	2.8	3.0	3.7	4.1
	Conversion	94.7%	99.9%	99.5%	99.7%
	Tailpipe	0.150	0.003	0.020	0.014
	TP Composite		0.010		
	EO Composite		3.0		
	Composite Conversion		99.7%		
FUL Compliance	FUL Durability Loss Margin	0.7%	0.5%	0.5%	1.0%
	FUL Conversion	93.9%	99.4%	99.0%	98.7%
	FUL Tailpipe	0.171	0.018	0.039	0.055
	FUL Composite Conversion		99.1%		
	IRAF		0.004	0.004	0.007
	Final TP Composite		0.030	0.043	0.062
	Margin to Standard		26%	-7%	38%
			0.010	-0.003	0.038

FIGURE 96. COMPLIANCE MARGIN CALCULATIONS FOR TEAM 2 PACKAGE 2 (NON-LOSCR) SYSTEM FOR 12,000 HOUR FUL

		NRTC			
		5%	95%		
		Cold	Hot	RMC	LLC
		g/kw-hr	g/kw-hr	g/kw-hr	g/kw-hr
	Standard	**0.04**		**0.04**	**0.10**
Certification Targets	Engine-Out	2.8	3.0	3.7	4.1
	Conversion	**94.7%**	**99.9%**	**99.5%**	**99.7%**
	Tailpipe	**0.150**	**0.003**	**0.020**	**0.014**
	TP Composite		**0.010**		
	EO Composite		**3.0**		
	Composite Conversion		**99.7%**		
FUL Compliance	FUL Durability Loss Margin	**0.4%**	**0.3%**	**0.3%**	**0.7%**
	FUL Conversion	**94.2%**	**99.6%**	**99.2%**	**99.0%**
	FUL Tailpipe	0.162	0.012	0.031	0.042
	FUL Composite Conversion		**99.3%**		
	IRAF		0.004	0.004	0.007
	Final TP Composite		**0.024**	**0.035**	**0.049**
	Margin to Standard		**41%**	**11%**	**51%**
			0.016	**0.005**	**0.051**

FIGURE 97. COMPLIANCE MARGIN CALCULATIONS FOR TEAM 2 PACKAGE 2 (NON-LOSCR) SYSTEM FOR 8,000 HOUR FUL

Note that the compliance margin looks good on the NRTC and LLC, and in addition this system would reduce CO_2 by 3% and 7% respectively. The temperature improvements introduced by the inclusion of CDA technology have helped to offset the impact of higher engine-out NO_X resulting from the revised calibration to reduce CO_2. However, the RMC would need more work, as neither projection has enough margin to even meet the minimum target of 25%, and in the case of the 12,000-hour target the projection is that the system would be above the standard at FUL. There were earlier indications is noted above that this value could likely be improved somewhat in calibration. However, even with some improvement it is likely that this still indicates that the Package 2 system will require more technology, and this could come in the form of the adoption of the dual SCR dual dosing option discussed earlier This will be examined in more detail during the continuing program efforts.

4.0 SUMMARY AND CONCLUSIONS

The objective of this program was works towards demonstrating the technical feasibility of reaching Low NO_X levels while demonstrating pathways to either GHG neutrality or a reduction in CO_2 emissions. The program goal for Low NO_X was 0.04 g/kW-hr over the NRTC and RMC cycles, with LLAC and in-use emissions as low as feasible. Two pathways were examined, which were designated as Package 1 and Package 2. For Package 1 the GHG goal was defined as at least maintaining CO_2 emissions and fuel consumption at a level comparable to the Baseline engine. For Package 2 the goal was to improve CO_2 levels by 5 to 8.5% from the Baseline engine. In both cases, the program intent was to reach these targets with technologies that were feasible for production by the 2028/9 MY range. The results of the program are summarized below, along with conclusions regarding those results with respect to the program targets. It should be noted that efforts are continuing to complete the supporting data set under the follow on program in CARB Contract 20MSC005, which will include further examination of more CO2 reduction options, and a more rigorous evaluation of emissions durability using the DAAAC protocol.

4.1 Demonstration Results

A summary of the key demonstration test results is given below in Figure 98 for tailpipe NO_X emissions for both technology packages compared to the baseline engine. Both packages achieve substantial reductions of 90% in tailpipe NO_X on the NRTC, 75% on the RMC, and more than 99% on the LLAC where tailpipe NO_X was reduced by two orders of magnitude compared to the base Tier 4 engine. It should be noted that the Low NO_X results are for Development Aged parts that were hydrothermally aged to FUL, while the baseline results are from only a de-greened system.

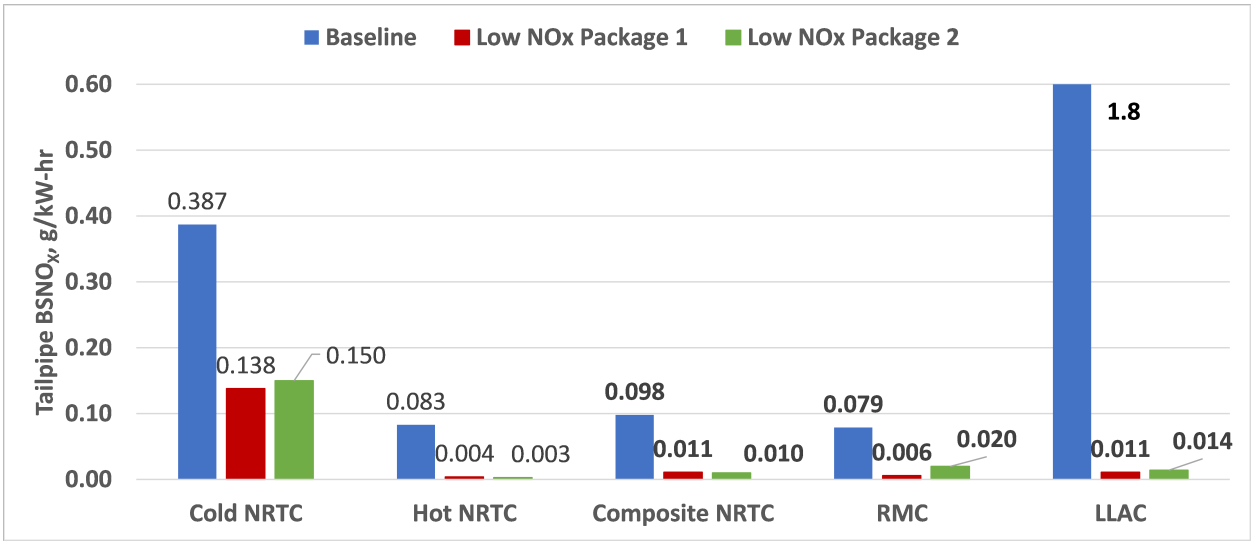


FIGURE 98. SUMMARY OF TAILPIPE BSNOX FOR LOW NOX PACKAGES COMPARED TO BASELINE

These results were all obtained with an aftertreatment architecture that was essentially an advanced version of the conventional DOC+DPF+SCR+ASC architecture that is already in production for many Tier 4 Final engines. Another key piece of the architecture for reaching these levels was the adoption of a CCV system. An important element of the NO_X result is the projected

compliance margin to a possible emissions standard from these packages at the end of FUL. These are summarized in Table 21 for both packages at both 8,000-hour and 12,000-hour FUL targets. For the NRTC and RMC a possible standard of 0.04 g/kW-hr was used for margin calculations, while a possible standard of 0.10 g/kW-hr was used for margin calculations. It should be noted that these values represent the projected margin available after accounting for projected performance losses due to aging and the impact of infrequent regeneration. For this program two scenarios were examined, a 25% margin scenario and a high margin scenario with a 50% projected compliance margin. Nearly all configurations met the 25% scenario, except that the current Package 2 calibration was below the 25% scenario on the high-load RMC cycle. However, it is expected that this scenario can be achieved with the additional calibration work planned in the follow on contract. The Package 1 system at 8,000 hours essentially was within the 50% margin, scenario and Package 2 came close to that 50% margin scenario at 8,000 hours on the NRTC and LLAC. At 12,000 hours FUL, none of the package projections in this program could quite reach the 50% margin scenario. However, additional technologies will be evaluated in the follow on program under 20MSC005 that may be able to reach this scenario.

TABLE 21. SUMMARY OF PROJECTED NO_X COMPLIANCE MARGINS TO POSSIBLE STANDARDS AT END-OF-LIFE FOR DIFFERENT TEST CONFIGURATIONS

Configuration	FUL	NO_x Compliance Margin, % of Standard		
	hours	NRTC	RMC	LLAC
Low NO_x Package 1	8,000	45	56	53
Low NO_x Package 1	12,000	32	43	41
Low NO_x Package 2	8,000	41	11	51
Low NO_x Package 2	12,000	26	-7	38
Standard Used for Projections, g/kW-hr		0.04	0.04	0.10

As noted earlier, the use of a CCV system was an integral part of reaching the compliance margins shown above in Table 21. If an open crankcase system (OCV) was used, the compliance margins would significantly smaller, by about 20% on the NRTC and RMC, and by about 10% on the LLAC.

A summary of the key GHG emission impacts for this engine as compared to the Baseline is given in Figure 99 for CO_2, and in Figure 100 for N_2O. Methane levels are extremely low from this diesel engine, essentially negligible in all three configurations, and therefore are not shown. For Package 1 the GHG goal was to be neutral compared to the baseline engine. The Package 1 results indicate that CO_2 was generally 0.4 to 1% lower than the Baseline, and the N_2O emissions were generally equivalent to the Baseline engine. The LLAC did show some increase in N_2O over the base engine, but the level seen would still be below the equivalent of the on-road standard level, and it should be noted that this is paired with a two order of magnitude reduction in NO_X. For Package 2 the target was a reduction of between 5% and 8.6% from the Baseline. The results indicated CO_2 reductions of nearly 4% on the NRTC and RMC, and nearly 8% on the LLAC. This is slightly below the target for the NRTC and RMC, but work efforts in the continuing demonstration program will examine potential for further CO_2 reductions. Package 2 did show a

small increase in N_2O on the NRTC, but as noted earlier, the levels seen are still well below any of the equivalent standards for on-road engines.

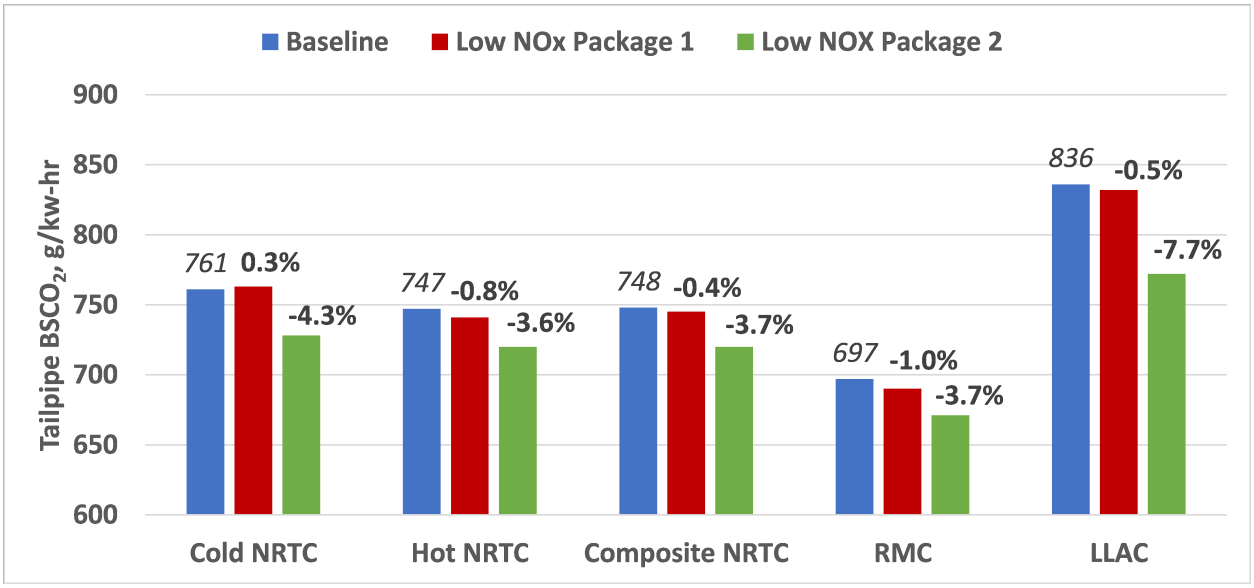


FIGURE 99. SUMMARY OF TAILPIPE $BSCO_2$ FOR LOW NO_X PACKAGES COMPARED TO BASELINE

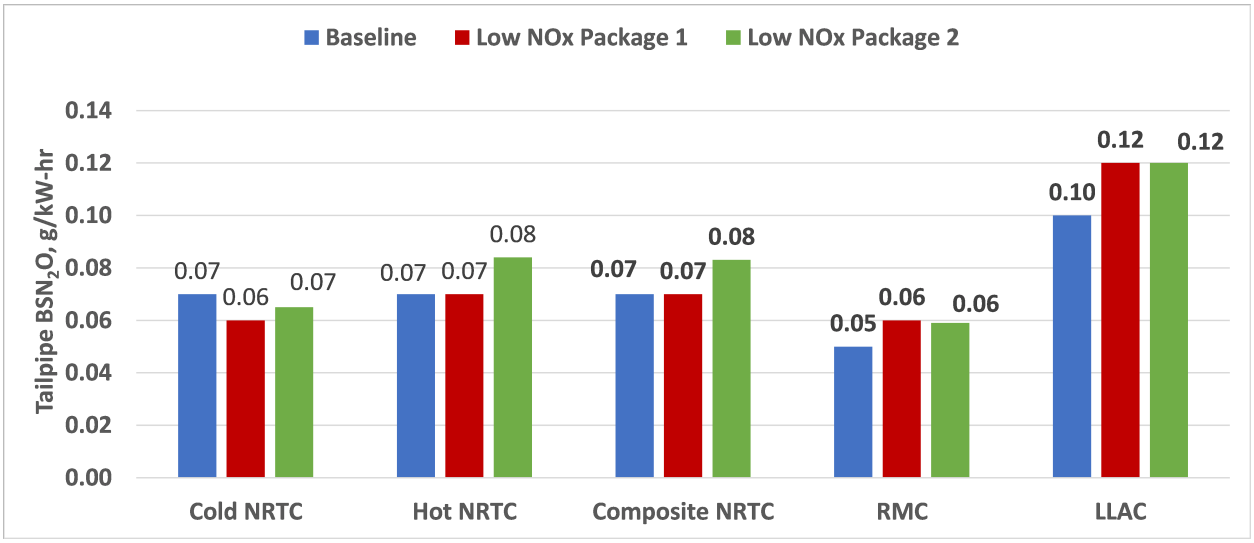


FIGURE 100. SUMMARY OF TAILPIPE BSN_2O FOR LOW NO_X PACKAGES COMPARED TO BASELINE

4.2 Additional Discussion of Technology Considerations and Feasibility

The test results discussed above and the projected compliance margins for different technology packages are a primary component of assessing the feasibility of a given set of standards. The emission results provided document of the potential performance of various technology options for meeting the emission targets outlined by possible future standards. However, performance and emissions performance durability are not the only considerations for determining the feasibility of various technologies.

The AT system packages that were evaluated and produced the results within this report, generally consist of technology which already in production. The basic architecture of the AT systems evaluated is still a conventional DOC+DPF+SCR+ASC arrangement, and conventional (unheated) DEF dosing was still utilized. The catalyst coating technology and formulations represent advancements from current Tier 4 Final production technology, but some of these formulations are already making their way into production in the on-road market for the 2021 MY and beyond. In a similar fashion, all of the sensors used in the program are currently available production units.

The engine calibrations produced by SwRI on the base engine were evaluated leveraging help from the program's partner engine manufacturer to address any potential issues in production deployment. Additional performance checks, such as load response tests, were run according to proprietary methodology to document that the modified calibrations maintained acceptable engine performance.

Packaging of the aftertreatment is a significant issue in any market, but it is especially important in the off-road market due to the wide variety of applications that the system must fit into. SwRI worked with canners experienced in fabricating current production off-road AT systems in developing the technology packages that were examined. Although the systems are larger than current Tier 4 hardware it should be noted that the SCR hardware was only slightly larger at a 12-inch diameter compared to the stock system 11-inch diameter. Overall, the displacement of the SCR system was roughly 22 liters versus the stock system at a little under 20 liters, representing a 14% increase, which was felt to be manageable. The DOC+DPF part of the system was larger, but was roughly the same length as the stock system although with a 2.5 inch larger diameter. Although single module design was used featuring an integrated compact mixer, designs were also available to split the system into two cans for packaging using a small, insulated u-pipe or elbow featuring the DEF doser and mixer. There will be challenges in packaging these larger components, but the overall increase in system size is considerably less than what was seen for the Stage 3 on-road program.

The step of moving to a closed crankcase ventilation (CCV) system also requires some discussion with regard to feasibility. It should be noted that while CCV is often employed on smaller diesel engines in the on-road market, there are durability risks of long-term turbocharger compressor and intake sensor fouling with adoption CCV. Improved filtration, including more efficient media, more frequent filter changes, and diagnostics would be required to support CCV adoption on most applications.[11] It should be noted that some of these systems are already in production in other markets. The variation and complexity due of the Off-road market do make this adoption more of a challenge.

The use of CDA (and DSF) in Package 2 provided both CO_2 and NO_X benefits, although the amount of benefit varied with duty cycle, as expected. As is the case in the on-road market, CDA does comes with vibration challenges that must be addressed through engineering. This can be done, but it should be noted that the off-road market contains a much wider variety of installation and mounting situations than what is seen for on-road trucks. This variety means that many more iterations of mounting and machine vibration environments must be evaluated, increasing the complexity of deploying this technology across the full range of engines. This increased complexity does increase the cost associated with adopting the technology, which must be considered along with the fact that the fuel savings are somewhat smaller due to the higher load

factor for most off-road applications. Fuel cost is also not as powerful a commercial driver in off-road markets as in on-road markets like Class 8 trucks, due to the smaller quantities of fuel that are burned.

It should be noted there are a number of other technology options for achieving the Package 2 goals of reducing CO_2 by 5% to 8.6%. Several of these options were evaluated for inclusion in this program and the continuing program efforts, but they were not included for reasons of scope and/or budget limitations. These includes options such as:

- Increasing compression ratio higher than the 17.6:1 of the stock engine. It should be noted that on-road engines run 19:1 or more, although this requires engine re-design to support much higher peak cylinder pressures.
- Engine friction reduction
- Electrified accessories
- 48V options such as an EGR pump (which allows moving to a more efficient single stage fixed geometry turbocharger), or an e-turbo
- Partially electrified and other hybrid powertrains in many applications deliver at least this level of savings, and more in some applications, and these may become applicable for some machines depending on the specifics of future regulations

Many of these options have not yet seen as wide an adoption on off-road markets, while others are already seeing examples implemented in certain machine applications.

5.0 RECOMMENDATIONS

Given the program results and conclusions presented earlier, a number of recommendations can be made regarding areas for further research and development. These additional recommended investigations would be useful to augment the initial conclusions from this report. It should be noted that some of these steps are already planned in the continuing program under CARB contract 20MSC005.

- The completion of efforts under that continuing contract are necessary to provide a complete technical demonstration. In particular, the Final Aging of the emission control system using the DAAAC protocol methodology is an essential step for the completion of the demonstration. The current conclusions regarding end-of-life performance are based on projections using prior experience from the on-road Stage 3 program, but actual data on the final system is needed.
- While the LLAC emission results are informative regarding low load emission controls, development of a fully representative off-road Low Load Cycle to address low load emissions for the off-road market will be important, to ensure that low load emission are addressed.
- Given the observed importance of controlling crankcase emissions to the final demonstrated performance, it is recommended that a characterization of crankcase emissions should be performed on the current engine. This should include both measurements on the current system and potential improved technologies to help ensure robust filtration that is able to protect the turbocharger compressor and intake sensors. This assessment would be intended to provide a technical feasibility demonstration of moving to closed crankcase ventilation (CCV), and would ideally include a durability demonstration using upgraded technology.

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APPENDIX - EMISSION DATA SUMMARIES

PACKAGE 1 – TEAM 2, OCV

TAILPIPE

ENGINE-OUT

		NRTC							
		Cold	Hot 1	Hot 2	Hot 3	Composite	Hot-Avg	LLAC	RMC
THC	g/kW-hr	0.15	0.07			0.07	0.07	0.43	0.05
NMHC	g/kW-hr	0.14	0.09			0.09	0.09	0.42	0.05
CO	g/kW-hr	1.8	1.5			1.5	1.5	2.0	0.4
NOx	g/kW-hr	2.1	2.3			2.3	2.3	3.9	2.6

PACKAGE 1 TEAM 2 - CCV

TAILPIPE

		NRTC							
		Cold	Hot 1	Hot 2	Hot 3	Composite	Hot-Avg	LLAC	RMC
THC	g/kW-hr	0.013	0.000	0.000	0.001	0.001	0.000	0.174	0.001
NMHC	g/kW-hr	0.013	0.000	0.000	0.001	0.001	0.000	0.087	0.001
CO	g/kW-hr	0.238	0.025	0.027	0.060	0.035	0.037	1.421	0.017
NOx	g/kW-hr	0.138	0.005	0.004	0.004	0.011	0.004	0.011	0.012
PM	g/kW-hr	0.0008	0.0007	0.0006	0.0009	0.0007	0.0007	0.0012	0.0006
CO2	g/kW-hr	760.7	741.8	740.5	740.9	742.7	741.0	832.2	685.0
Work	kW-hr	23.99	23.95	23.93	23.92	24.0	23.93	34.91	51.87
N2O	kW-hr	0.061	0.075	0.077	0.076	0.074	0.076	0.121	0.051
CH4	kW-hr	0.001	0.000	0.000	0.000	0.000	0.000	0.092	0.000

ENGINE-OUT

		NRTC							
		Cold	Hot 1	Hot 2	Hot 3	Composite	Hot-Avg	LLAC	RMC
THC	g/kW-hr	0.17	0.07	0.09	0.09	0.08	0.09	0.45	0.04
NMHC	g/kW-hr	0.17	0.09	0.07	0.09	0.10	0.09	0.45	0.04
CO	g/kW-hr	1.5	1.4	1.4	1.4	1.4	1.4	2.1	0.4
NOx	g/kW-hr	2.3	2.4	2.4	2.4	2.4	2.4	4.0	2.6

PACKAGE 2 – TEAM 2 WITH CDA - CCV

TAILPIPE

		NRTC							
		Cold	Hot 1	Hot 2	Hot 3	Composite	Hot-Avg	LLAC	RMC
THC	g/kW-hr	0.010	0.001	0.000	0.000	0.002	0.000	0.000	0.000
NMHC	g/kW-hr	0.009	0.001	0.000	0.000	0.002	0.000	0.000	0.000
CO	g/kW-hr	0.232	0.069	0.031	0.029	0.077	0.043	0.064	0.018
NOx	g/kW-hr	0.143	0.004	0.004	0.003	0.011	0.004	0.005	0.020
PM	g/kW-hr	0.0009	0.0006	0.0008	0.0007	0.0006	0.0007	0.0004	0.0003
CO2	g/kW-hr	747.8	727.0	727.8	725.1	728.0	726.6	778.7	670.9
Work	kW-hr	23.95	23.90	23.89	23.87	23.9	23.89	34.87	51.85
N2O	kW-hr	0.064	0.081	0.081	0.081	0.080	0.081	0.118	0.059
CH4	kW-hr	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000

ENGINE-OUT

		NRTC							
		Cold	Hot 1	Hot 2	Hot 3	Composite	Hot-Avg	LLAC	RMC
THC	g/kW-hr	0.13	0.05	0.07	0.07	0.06	0.07	0.00	0.00
NMHC	g/kW-hr	0.13	0.07	0.05	0.07	0.07	0.06	0.00	0.00
CO	g/kW-hr	1.5	1.4	1.4	1.4	1.4	1.4	0.0	0.0
NOx	g/kW-hr	2.7	2.8	2.8	2.8	2.8	2.8	0.0	0.0

PACKAGE 2 – TEAM 2 WITH DSF - CCV

TAILPIPE

		NRTC							
		Cold	Hot 1	Hot 2	Hot 3	Composite	Hot-Avg	LLAC	RMC
THC	g/kW-hr	0.009	0.000	0.000	0.000	0.000	0.000	0.004	0.000
NMHC	g/kW-hr	0.009	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CO	g/kW-hr	0.239	0.024	0.030	0.027	0.035	0.027	0.048	0.018
NOx	g/kW-hr	0.150	0.002	0.005	0.004	0.009	0.004	0.014	0.020
PM	g/kW-hr	0.0008	0.0005	0.0006	0.0007	0.0005	0.0006	0.0012	0.0004
CO2	g/kW-hr	746.7	720.3	719.5	718.9	721.6	719.5	772.6	670.9
Work	kW-hr	23.94	23.92	23.87	23.86	23.9	23.88	34.72	51.85
N2O	kW-hr	0.065	0.081	0.085	0.085	0.080	0.084	0.142	0.059
CH4	kW-hr	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.000

ENGINE-OUT

		NRTC							
		Cold	Hot 1	Hot 2	Hot 3	Composite	Hot-Avg	LLAC	RMC
THC	g/kW-hr	0.22	0.15	0.20	0.20	0.15	0.18	0.38	0.04
NMHC	g/kW-hr	0.21	0.20	0.14	0.20	0.20	0.18	0.37	0.04
CO	g/kW-hr	1.8	1.8	1.9	1.9	1.8	1.9	1.4	0.3
NOx	g/kW-hr	2.8	3.0	3.0	3.0	3.0	3.0	4.4	3.7

PACKAGE 2 – TEAM 2 - CCV

TAILPIPE

		NRTC							
		Cold	Hot 1	Hot 2	Hot 3	Composite	Hot-Avg	LLAC	RMC
THC	g/kW-hr	0.009	0.000	0.000	0.001	0.000	0.000	0.000	0.017
NMHC	g/kW-hr	0.008	0.000	0.000	0.001	0.000	0.000	0.000	0.017
CO	g/kW-hr	0.191	0.060	0.096	0.071	0.067	0.076	0.047	0.019
NOx	g/kW-hr	0.150	0.006	0.007	0.006	0.013	0.006	0.016	0.020
PM	g/kW-hr	0.0009	0.0007	0.0009	0.0007	0.0007	0.0007	0.0013	0.0005
CO2	g/kW-hr	746.8	726.7	725.9	726.4	727.7	726.3	834.1	677.8
Work	kW-hr	24.03	23.98	23.95	23.95	24.0	23.96	34.92	51.87
N2O	kW-hr	0.063	0.074	0.077	0.078	0.073	0.076	0.121	0.078
CH4	kW-hr	0.000	0.000	0.001	0.000	0.000	0.000	0.002	0.000

ENGINE-OUT

		NRTC							
		Cold	Hot 1	Hot 2	Hot 3	Composite	Hot-Avg	LLAC	RMC
THC	g/kW-hr	0.13	0.06	0.08	0.08	0.06	0.07	0.46	0.05
NMHC	g/kW-hr	0.12	0.08	0.06	0.08	0.08	0.07	0.46	0.05
CO	g/kW-hr	1.4	1.3	1.3	1.3	1.3	1.3	1.9	0.3
NOx	g/kW-hr	2.6	2.8	2.8	2.8	2.8	2.8	3.9	3.7