

**NEXT TIER OFF-ROAD DIESEL
TECHNOLOGY SELECTION, CALIBRATION, AND
FINAL DEMONSTRATION**

**OFF-ROAD LOW NOX DEMONSTRATION
PROGRAM - STAGE 3 ADDENDUM
FIELD CYCLE PERFORMANCE**

**ARB CONTRACT 20MSC005
AMENDMENT 2**

FINAL REPORT

SwRI® Project Number 03.26778

Prepared for:

California Air Resources Board

Prepared by:

Christopher A. Sharp, Institute Engineer - Program Manager

**Southwest Research Institute
6220 Culebra Road
San Antonio, TX 78238**

September 12, 2025



Benefiting government, industry and the public through innovative science and technology

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POWERTRAIN ENGINEERING DIVISION

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LIST OF ACRONYMS

°C	Degrees Celsius
%	Percent
40 CFR	Title 40, Code of Federal Regulations
2B-MAW	2-Bin Moving Average Window
3B-MAW	3-Bin Moving Average Window
ASC	Ammonia Slip Catalyst
AT	Aftertreatment
B-MAW	Bin-Moving Average Window
BMEP	Brake Mean Effective Pressure
BSCO ₂	Brake Specific Carbon Dioxide
BSN ₂ O	Brake Specific Nitrous Oxide
BSNO _x	Brake Specific Oxides of Nitrogen
CAN	Controller Area Network
CARB	California Air Resources Board or Board
CDA	Cylinder Deactivation
CF	Conformity Factor
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
CPSI	Cells per Square Inch
CSF	Catalyzed Soot Filter
Cu-Ze	Copper-Zeolite
DAAAC	Diesel Aftertreatment Accelerated Aging Cycles
DEF	Diesel Exhaust Fluid (32% urea by weight)
DF	Deterioration Factor
dDSF	Diesel Dynamic Skip Fire
dsSCR	Downstream SCR
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
DSF	Dynamic Skip Fire
ECM	Electronic Control Module
ECT	Engine Coolant Temperature
EGR	Exhaust Gas Recirculation
EMA	Truck and Engine Manufacturers Association
FE	Fuel Economy
FTIR	Fourier Transform Infrared Spectroscopy
FTP	U.S. Heavy Duty Transient Federal Test Procedure
g/hr	Grams per Hour
g/kW-hr	Grams per Kilowatt-Hour
hp	Horsepower
hr	Hour
in	Inch
IRAF	Infrequent Regeneration Adjustment Factor
JVS	Jacobs Vehicle Systems

H/W	Hardware
kW	Kilowatt
L	Liter
LLC	Low Load Cycle
LLAC	Low Load Application Cycle
LO-SCR	Light Off SCR Catalyst
M/C	Machine
MAB2	MicroAutoBox II
MAW	Moving Average Window
MECA	Manufacturers of Emission Controls Association
MFC	Multi-Function Catalyst (LO-SCR)
mg/kW-hr	Milligrams per Kilowatt-Hour
mm	Millimeter
N ₂ O	Nitrous Oxide
NH ₃	Ammonia
Nm	Nanometer
NO	Nitric Oxide
NO ₂	Nitrogen Dioxide
NO _x	Oxides of Nitrogen
NRTC	Nonroad Transient Cycle
PEMS	Portable Emissions Measurement System
PM	Particulate Matter
RMC	Ramped Modal Cycle
RMC-C1	Ramped Modal Cycle C-1 8-Mode for Variable Speed Nonroad Engines
RMC-SET	Ramped Modal Cycle Supplemental Emission Test
rpm	Revolutions per Minute
SCR	Selective Catalytic Reduction (ammonia-based)
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
UAF	Upward Adjustment Factor (for Infrequent Regeneration)
xB-MAW	Bin Moving Average Window (x = 2 and/or 3)
zCSF	Zone-coated Catalyzed Soot Filter

ABSTRACT

The work effort documented by this report is an addition to previously reported efforts to demonstrate the feasibility of technologies to reach tailpipe oxides of nitrogen emission reductions of up to 90 percent (%) from the current Tier 4 final standards, and particulate matter emission reductions of at least 75% from the current Tier 4 final standards. This additional work was aimed at expanding the scope of the original technology demonstration to encompass field duty cycles from real-world applications, in addition to the regulatory lab cycles that are typically used for emission certification and compliance testing. This effort leveraged the Package 2 Tier 5 demonstration engine-aftertreatment system that was developed under the California Air Resources Board (CARB) Contract 20MSC005. A number of field duty cycles were developed in partnership with CARB staff, based on application data that was originally recorded in the field for various off-road applications. Each data set represented a full shift-day of operation for a given machine, starting from initial cold-start. The field data sets were translated into normalized duty cycles that could be run on an engine dynamometer, allowing for evaluation of the performance of the Tier 5 demonstration engine over real-world duty cycles. These duty cycles were examined using the full useful life emission control system, which was aged to the equivalent of 8000 hours in the previous program. Both nominal or low power chid ratings of the engine were examined during this effort, and evaluations were conducted using both the base Tier 5 package and an alternate packaging arrangement. Testing was conducted both with and without the use of cylinder deactivation in the form of Dynamic Skip Fire. The Tier 5 demonstration generally performed well under these conditions, showing significant margins to proposed emission thresholds using the proposed bin-moving average window data analysis methods.

EXECUTIVE SUMMARY

Despite decades of progress in cleaning the air in California, challenges remain. The California Air Resources Board (CARB) has stated in the 2020 Mobile Source Strategy document that meeting federally mandated ozone limits in the National Ambient Air Quality Standard will require significant reductions in ozone forming oxides of nitrogen (NO_x) emissions across a wide range of applications. NO_x 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 further reductions from current standards are necessary to achieve air quality goals.

Previously, a series of programs were run on behalf of CARB at the Southwest Research Institute (SwRI) to demonstrate the technical feasibility of reaching Low NO_x levels up to 90 percent (%) below the current standards for on-highway engines [1][2][3][4][5][6]. In April 2024, the final report for the primary off-road Tier 5 demonstration program (Stage 3) under contract 20MSC005 was released [7]. The goal of that 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 to demonstrate a level below 0.040 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, 75% below the current Tier 4 final standard. At the same time, the target was also to have the system demonstrate reductions in carbon dioxide (CO_2) on the order of 5% to 8.6% (equivalent to Phase 1 on-highway greenhouse gas reductions) compared to the Tier 4 final baseline engine. The program's intent was to reach these targets with technologies that are feasible for production in the off-road market by model year 2029.

To expand the scope of the demonstration to examine in-use emissions and field duty cycles, it was necessary to develop a set of duty cycles that represented real-world in-use operations in a variety of different off-road applications. A large data set of operations was previously assembled for the development of the off-road Low Load Cycle, and this data set was used to provide the application data for field cycle development. However, the focus was not only on low load operations, but rather on identifying full shift-days or representative operation, regardless of overall load. SwRI evaluated candidate data sets provided by CARB staff, and 7 of these were selected for this program. Those 7 data sets were translated into normalized engine cycles that could be run on the Tier 5 demonstration engine. The final 7 cycles are illustrated in Figure 1 and Appendix A, with normalized speed in blue and normalized torque in red. The individual cycles are detailed more in the report, but this illustration serves to indicate the variety of different types of operations captured in this set of field cycles. All cycles started with a cold-start at the beginning of a test day, and two of the cycles (Cycle 01 and Cycle 07) included an engine shut down and restart in the middle of the

day. The cycles ranged in duration from 5.5 to 10 hours, and in average load from 11% to 43% of maximum power.

A visual summary of 2-bin Moving Average Window (2B-MAW) results for these cycles is given in Figure 2. The results show the 8000-hour aged Tier 5 system generally at or below half the placeholder Bin B threshold, with the exception of Cycle 14 without Dynamic Skip Fire (DSF), which has a margin of 11 milligrams per kilowatt-hour at a Conformity Factor (CF) of 1.5. Bin A results are below the proposed threshold by a factor of 20. A similar summary for 3-bin Moving Average Window (3B-MAW) results is given in Figure 3. When comparing the results in these two charts, it is worth noting that any of the field cycles that showed a higher value for either Bin B or Bin C in the 3-bin scenario generally also showed one of the higher Bin B values in a 2-bin scenario. This indicates that the 2-bin method appears to highlight cases with higher emissions just as well as the 3-bin method.

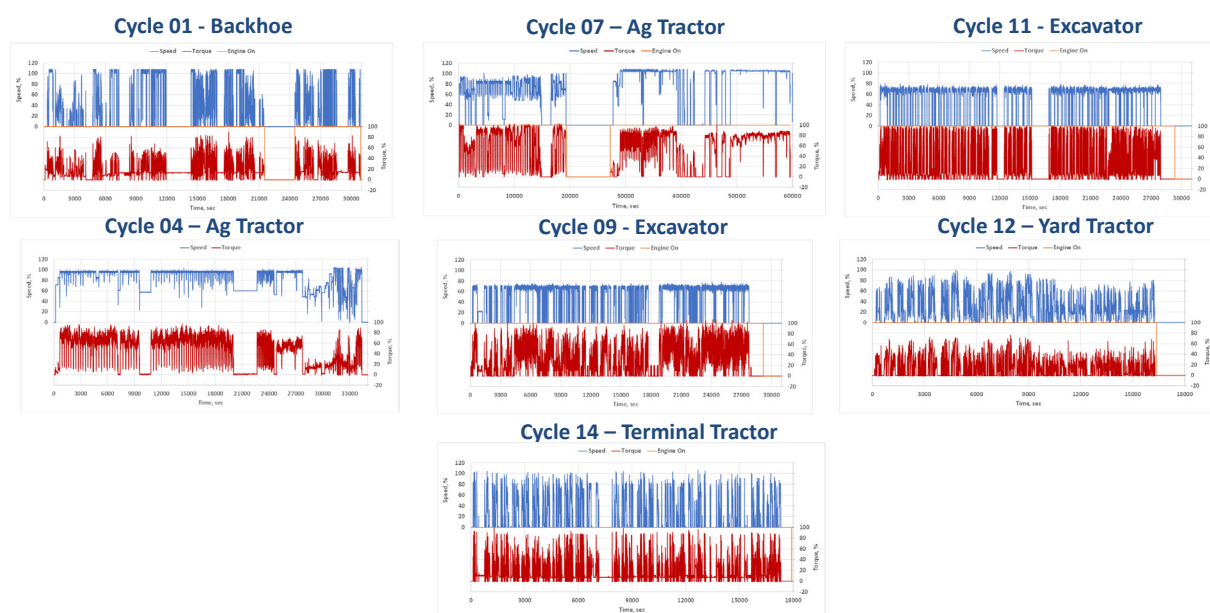
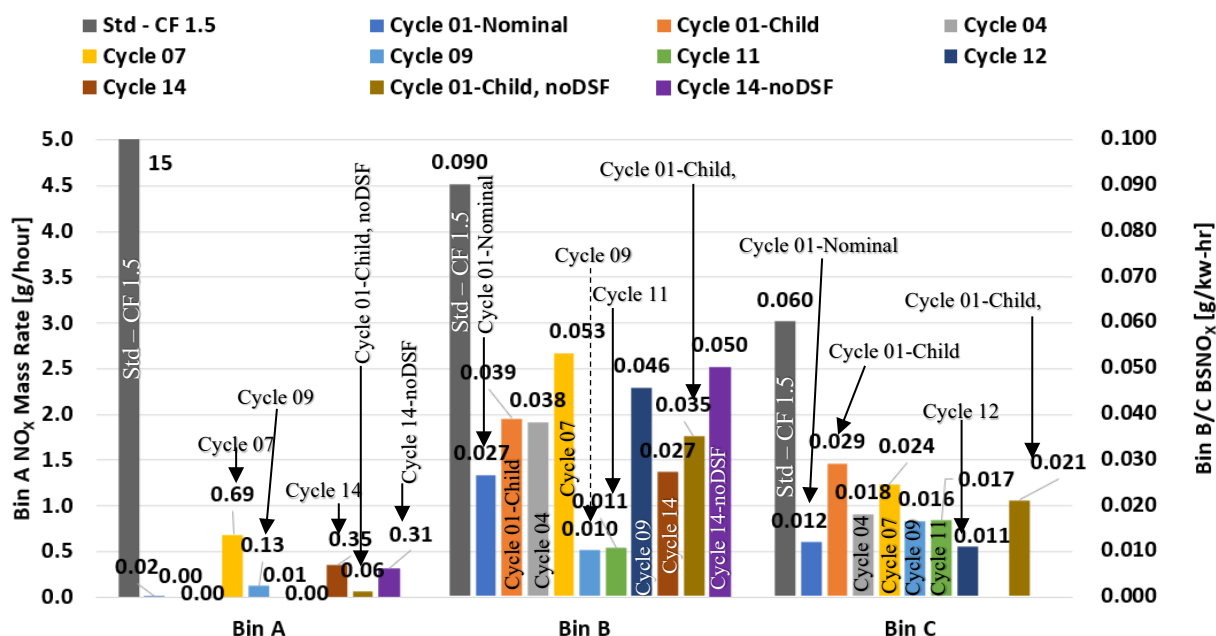
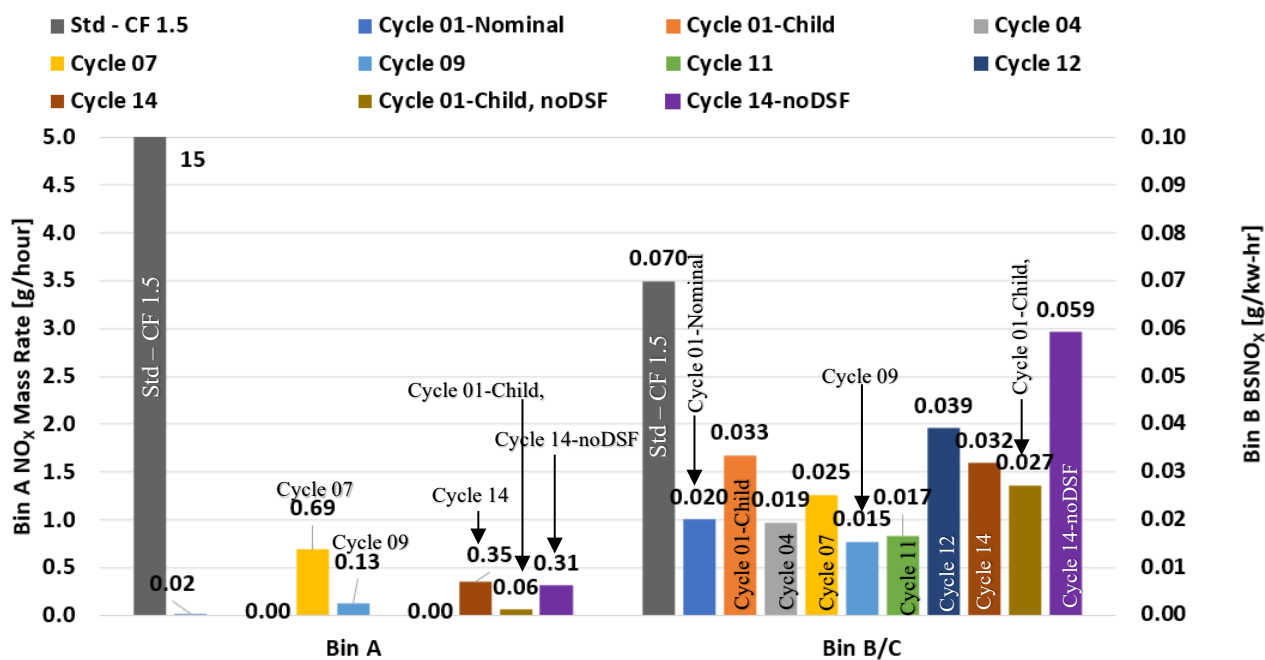


FIGURE 1. OFF-ROAD FIELD DUTY CYCLES BASED ON REAL-WORLD APPLICATION DATA

FIGURE 3. 3B-MAW NO_x EMISSION RESULTS FOR FIELD CYCLESFIGURE 2. 2B-MAW NO_x EMISSION RESULTS FOR FIELD CYCLES

Both CO₂-based and Torque-based calculations were examined for this effort. There was no clear trend in emission results in either 2B-MAW or 3B-MAW scenarios between the two calculations methods. The torque-based method demonstrated equivalence in identifying high emitters compared to the CO₂-based method.

However, it is important to consider the potential larger measurement errors at low loads when deciding to adopt a torque-based method.

1.0 INTRODUCTION AND BACKGROUND

This report details an extension of the Stage 3 Off-road Low NO_x Demonstration Program that was conducted at the Southwest Research Institute (SwRI), and is part of SwRI's continuing efforts to demonstrate low oxides of nitrogen (NO_x) emission control technologies for off-road diesel engines on behalf of the California Air Resources Board (CARB or Board) since 2018 [7][8][9]. The effort detailed herein comprises work to expand the demonstration scope previously reported under the Stage 3 Off-road program [7]. The scope of that program was expanded under Amendment 2 to Contract 20MSC005 to examine the capability of the Tier 5 demonstration system over a variety of real-world duty cycles. This was done to further document the robustness of the Tier 5 demonstration system, as well as to provide additional information to help CARB staff finalize decisions regarding future off-road in-use testing methodology and requirements.

This program leveraged experience and understanding that were gained during previous technology demonstration efforts conducted in support of the development of the CARB on-highway Low NO_x Omnibus rule, which was approved for adoption by the Board in August 2020. It is understood that the efforts documented in this report will be used to inform the development of Tier 5 for off-road diesel new engine standards in California. The proposed elements of the Tier 5 regulation were most recently released during a two-day workshop on October 30-31, 2023, and a workshop on October 8, 2024 [10].

To meet the goals of this expanded effort, several work tasks were performed:

- Several field duty cycles were developed based on real-world off-road machine data recorded in the field. These field cycles came from full shift-day operations on a variety of machines in different construction and agricultural applications from backhoes, agricultural tractors, excavators, off-highway yard tractors and terminal tractors.
- The field cycles run on the Tier 5 demonstration engine and aftertreatment (AT) package using the 8000-hour (hr) aged demonstration AT hardware, both with and without dynamic skip-fire (DSF) active.
- SwRI examined the need to make calibration adjustments based on the initial results
- The adjusted calibration was examined on the field cycles, as well as making sure that the change did not impact the regulatory cycle performance of the Tier 5 demonstration engine.
- Performance was examined using an alternate AT package previously developed by the Truck and Engine Manufacturers Association (EMA) using the same aged hardware in a different package arrangement

(described in Section 2.4.1 of this report) to represent different machine installations.

Field cycle data was analyzed using CARB's proposed 3-bin Moving Average Window (3B-MAW) methodology for off-road engines. In addition, several alternate approaches to the calculation of in-use emissions were also examined, including a 2-bin approach, and calculations based on both torque and carbon dioxide (CO₂) emissions (similar to the on-highway approach).

Over the course of this expanded effort, other issues were also examined. The off-road Low Load Cycle (LLC) and selected field cycles were also used to examine the impact of different idle load settings on system performance. In addition, a number of NO_x sensors were run in parallel with the field cycle tests in support of efforts under CARB Contract 22RD019 to examine the accuracy and capability of tailpipe NO_x sensors under these conditions.

2.0 METHODS AND MATERIALS

This section of the report details the engine test hardware, test methods, AT systems and controls that were utilized in this program. In addition, details of the in-use calculation methods that were used for data analysis are also given in this section.

2.1 Test Engine

The test engine for this program was a 2019 model year 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 kilowatt (kW) maximum power rating at 2200 revolutions per minute (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. The engine was later reinstalled for Low NO_x development and demonstration efforts under contracts 19RD025 and 20MSC005 [7][9]. 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

An additional lower power “child” rating of the engine was also used. A child rating is a lower torque curve calibration on the same hardware within an engine family. Child ratings are of interest here because they share the same absolute thermal mass and heat loss characteristics of the common hardware, but the lower power rating can result in less fuel supplied enthalpy through the system. For this engine, that lower power rating operated on the same engine and AT hardware had a rated power of 126 kW and a peak torque of 780 nanometers (Nm).

The nominal 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 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, diesel particulate filter (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 that was 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 Section 2.6 covering Low NO_x Controls.

The stock Deere AT system was a conventional DOC+DPF+SCR architecture, with the canning arrangement being two can “switchback” style assembly. The DOC (diesel oxidation catalyst) and DPF are in the first can followed by a dosing and mixing

tube, and finally a second can, containing the SCR (selective catalytic reduction) 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.



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 7. This test cell was a transient capable test cell meeting the requirements of Title 40, Code of Federal Regulations (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 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 total hydrocarbon (THC), methane, non-methane hydrocarbon, carbon monoxide (CO), CO₂, and NO_x. In addition to the Dilute measurements, a Fourier Transform Infrared Spectroscopy (FTIR) was also used in the Raw exhaust at the tailpipe to monitor nitric oxide (NO), nitrogen dioxide (NO₂), ammonia (NH₃), nitrous oxide (N₂O), and sulfur dioxide, as well as CO₂ 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 as 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, CO₂, NO_x, NO, and oxygen, as well as intake manifold CO₂ 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 and the chemical balance calculations in 40 CFR 1065.650 and 1065.655.

To support combustion and hardware development, a 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) actuation 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 recorded 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 a meaningful comparison of CO₂ emission results over the long performance periods and multiple systems of this program, tailpipe CO₂ 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 Section 4 covering the program results.

It was observed under this program that the day-to-day variability of tailpipe NO_x emissions for the various test cycles, as characterized by the standard deviation of the brake-specific results was in the range of ± 2 milligrams per kilowatt-hour (mg/kW-hr) for the Nonroad Transient Cycle (NRTC) and Ramped Modal Cycles (RMC), ± 3 mg/kW-hr for the Low Load Application Cycle (LLAC), and ± 5 mg/kW-hr for the LLC.

2.3 Test Cycles, Test Procedures, and Preconditioning Procedures

This work effort documented in this report was targeted primarily at the seven new field duty cycles. The field cycles that were run and their development are

described in more detail in Section 3 of this report. For consistency, a preconditioning process consisting of two hot-start NRTC cycles was run prior to the overnight soak before each field cycle run. These were always run using a cycle appropriate to the engine rating (126 kW or 187 kW) and configuration (with or without DSF) that would be tested the following day. All field cycles began with a cold-start the following morning.

For regulatory cycle evaluations, emission performance was demonstrated over the relevant off-road regulatory cycles, including the NRTC, RMC-C1, and the newly developed off-road LLC. The NRTC and RMC-C1 cycles are well documented in 40 CFR Part 1039 and are currently used for certification of Tier 4 engines. The off-road LLC was also part of the regulatory test cycle set used for this program, and the normalized off-road LLC is shown in Figure 7. This cycle was developed as part of the Stage 3 work under 20MSC005, and the development is described in detail in the report for that program [9]. A comparison of the average power of all of these cycles, in comparison to each other and the on-highway cycles is given in Table 2.

All testing and preconditioning were conducted in accordance with the procedures given in 40 CFR Part 1039 and 40 CFR Part 1065. 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 an 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-C1 was conducted as outlined in 40 CFR Part 1065, wherein an RMC-C1 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 the record.

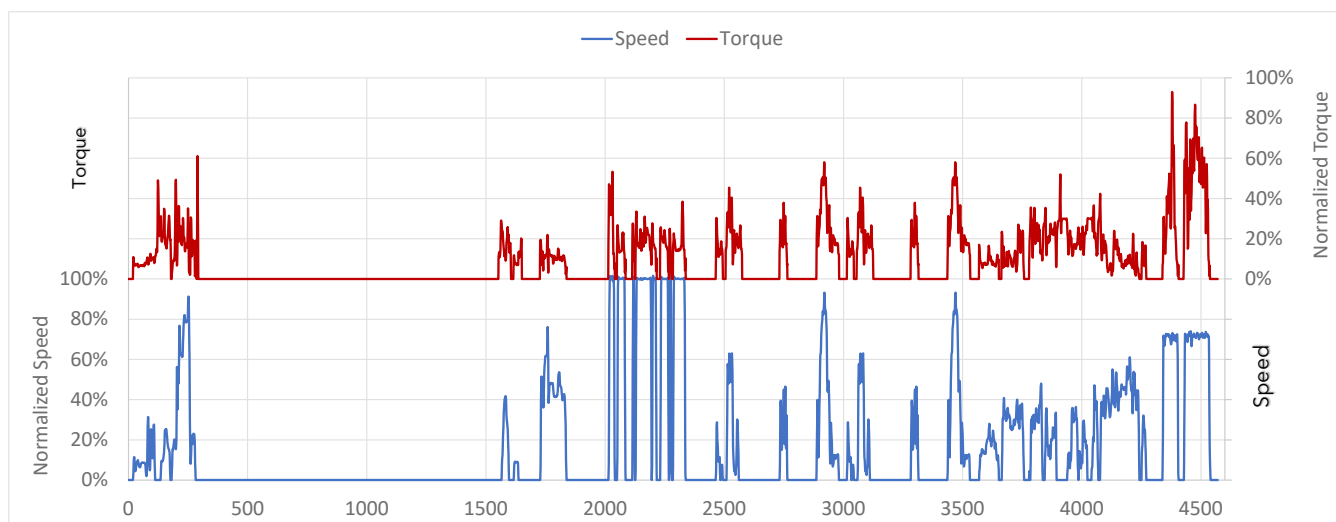


FIGURE 7. NORMALIZED OFF-ROAD LOW LOAD CYCLE (LLC)

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 C1	55%
Low Load	LLC	6 - 7 %	LLAC	15%
			LLC	10%

Preconditioning for the LLC involves running at least one hot-start NRTC transient cycle. 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 LLC, such that no additional engine operation is needed, and the LLC can be run following a 20-minute soak. However, in the event the sequence was interrupted, two preconditioning hot-start NRTC transient cycles would be run, followed by a 20-minute engine-off soak and then the LLC test itself, as noted earlier.

2.4 Low NO_x Aftertreatment Hardware

This final Tier 5 Low NO_x AT system is depicted below in Figure 8, and catalyst details for this system are given in Table 3. This system is shown installed in the test cell in Figure 9. Figure 10 shows the mounting of the heated doser and plenum mixer

assembly in the transfer tube from the engine, which was kept at the same total length as was used for the conventional architecture systems previously.

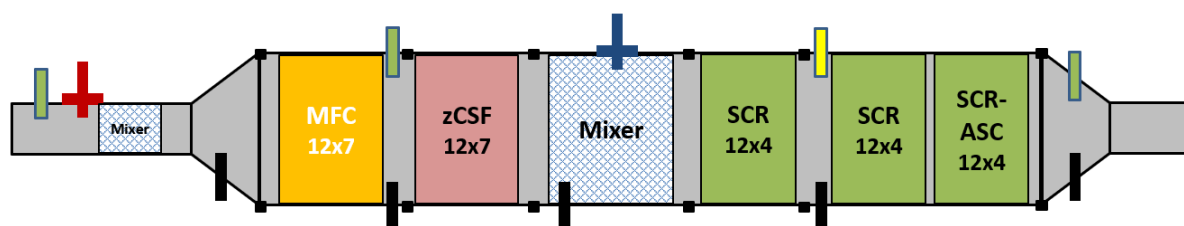


FIGURE 8. SCHEMATIC OF DUAL SCR DUAL DOSING ARCHITECTURE AFTERTREATMENT SYSTEM

TABLE 3. COMBINED SYSTEM CATALYST SPECIFICATIONS FOR DUAL DEF DOSER SYSTEM

Component	D x L, in	Cell Density, CPSI/Wall, mm	Volume	Notes
Multi-Function Catalyst (MFC) (LO-SCR)	12x7	400/4	13 L	2-in ASC layer at back
Zone-coated Catalyzed Soot Filter (zCSF)	12x7	300/7 ACT*	13 L	2-in DOC layer at front
SCR	12x4	600/4.5	7.5 L	Copper-Zeolite (Cu-Ze)
SCR	12x4	600/4.5	7.5 L	Cu-Ze
SCR-ASC	12x4	600/4.5	7.5 L	Cu-Ze, 2-ASC layer at back
*Asymmetric Cell Technology				

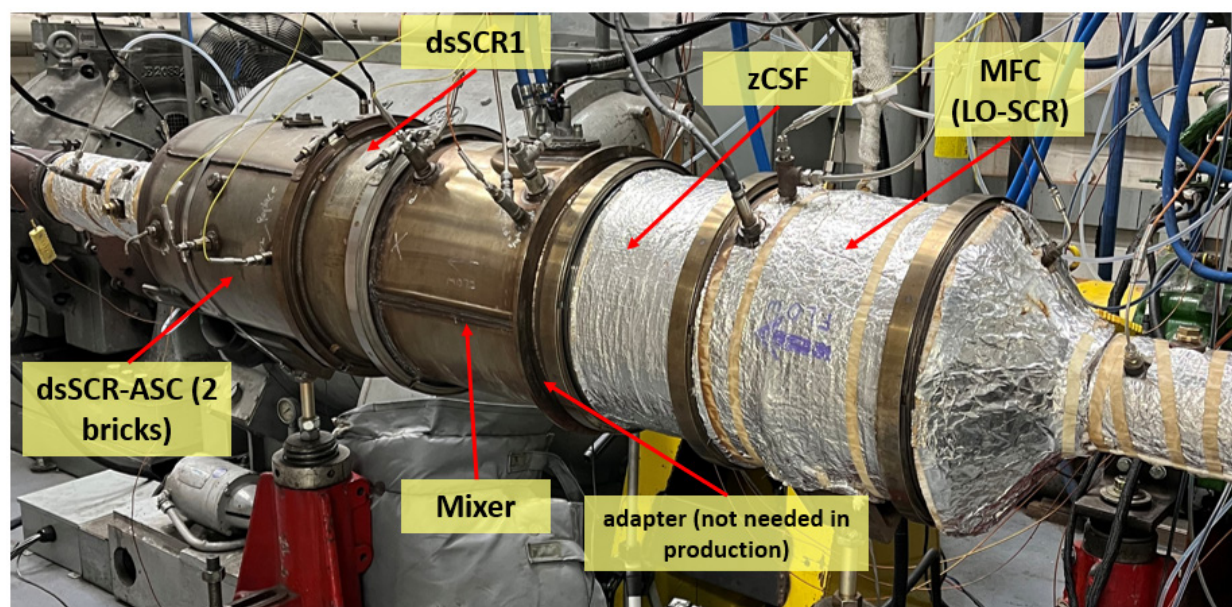


FIGURE 9. FINAL COMBINED AFTERTREATMENT SYSTEM WITH DUAL DOSING DUAL SCR ARCHITECTURE

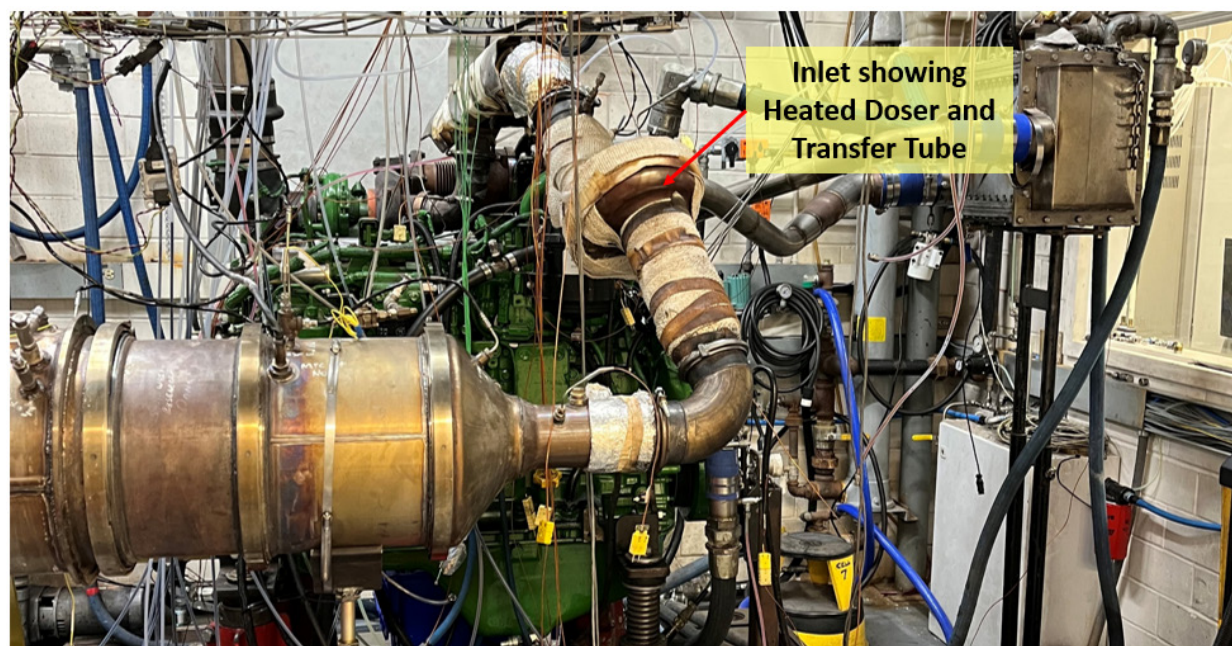


FIGURE 10. TRANSFER PIPE FROM ENGINE FOR DUAL DOSING DUAL SCR ARCHITECTURE SHOWING HEATED DOSER AND MIXER MOUNTING

2.4.1. Modified Aftertreatment Packaging Configuration

In addition to the base Tier 5 AT package described above, field cycle performance was also examined using a modified packaging arrangement. This modified package was developed as part of work efforts conducted on behalf of EMA using the Tier 5 demonstration platform. This modified packaging arrangement was developed originally to investigate the possible sensitivity of tailpipe NO_x performance to different package arrangements, which might be required to accommodate the wide variety of machine applications that an off-road engine might encounter.

The packaging changes are shown in the schematic given in Figure 11. The base Tier 5 package used a single inline AT module approach, while the alternate package broke the system into two separate cans that could be arranged in a variety of ways to accommodate the package requirements of different machines. The two different packages are shown in the test cell in Figure 12.

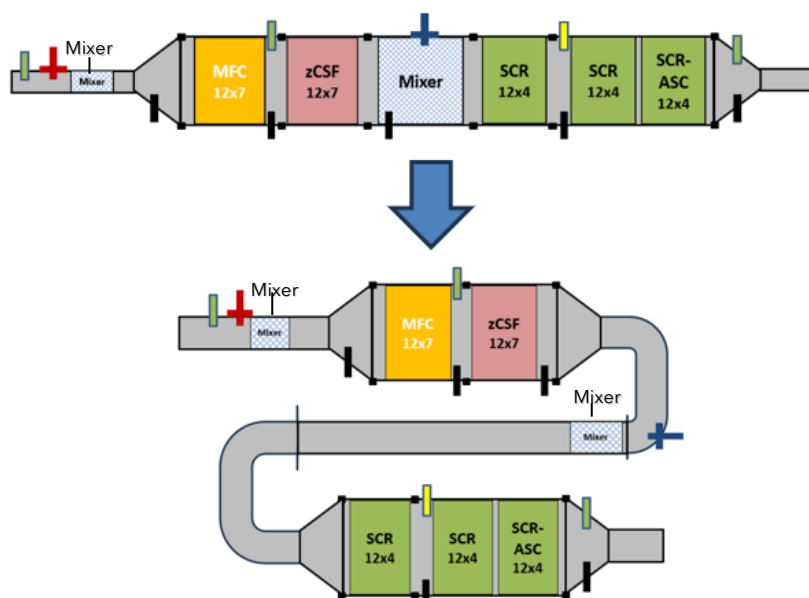
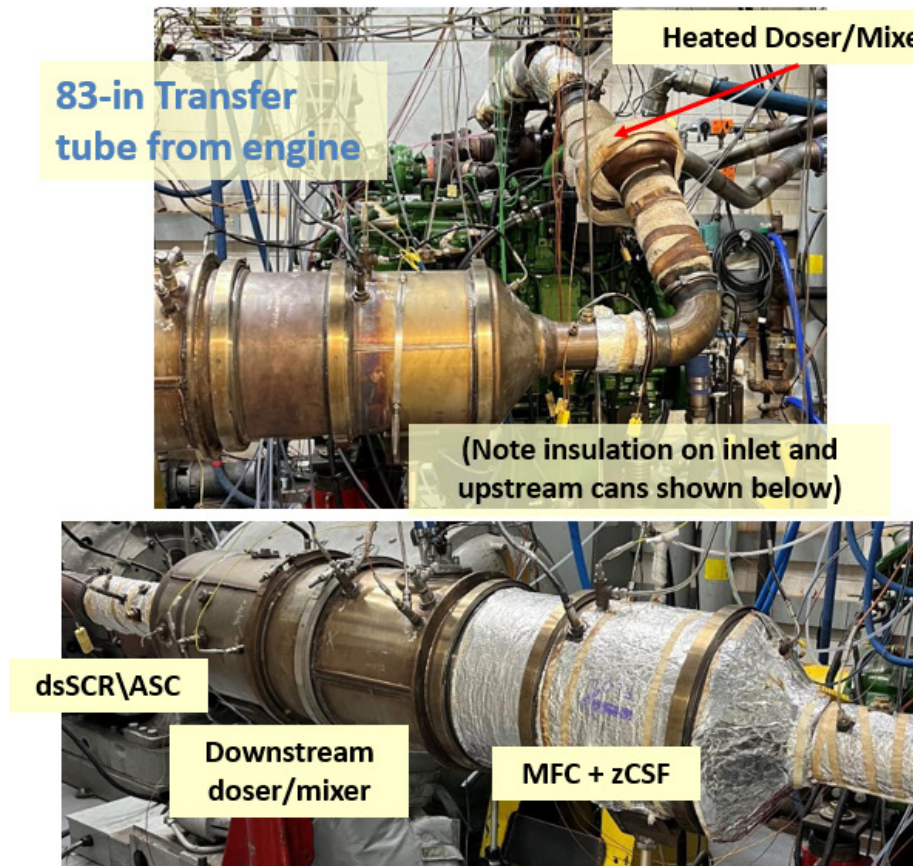


FIGURE 11. SCHEMATIC OF PACKAGE COMPARISON BETWEEN BASE TIER 5 AND ALTERNATE PACKAGE CONFIGURATIONS

Both configurations are considered representative of the kind of arrangements that would be seen in production applications, though it is anticipated that the Alternate package might actually be more common. It should be noted that the same system controls and calibrations were used for both packages.

Base Tier 5 (Single Module)



Alternate Package (2-Can)

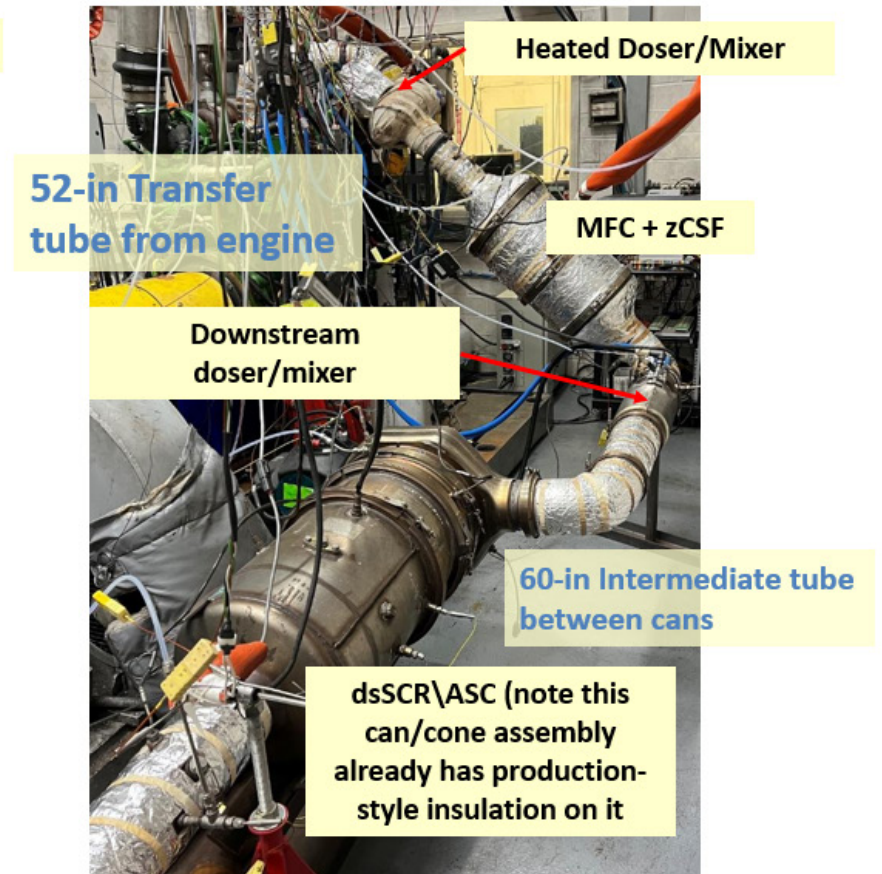


FIGURE 12. BASE TIER 5 AND ALTERNATE AFTERTREATMENT PACKAGING SHOWN IN THE TEST CELL ON THE ENGINE

2.5 Low NO_x Engine Hardware

2.5.1. *Cylinder Deactivation (CDA)*

The CDA system hardware used in this program was supplied by Jacobs Vehicle Systems (JVS). The system is shown below in Figure 13, installed on the Deere 6068 engine. As can be seen in the zoom-in figure at the bottom-right side of Figure 13, 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 DSF, as discussed below. The system was controlled via the dSPACE MAB2 integration controller that was deployed by SwRI, using software that was developed working with JVS for control, and a solenoid driver system developed by SwRI for this application.

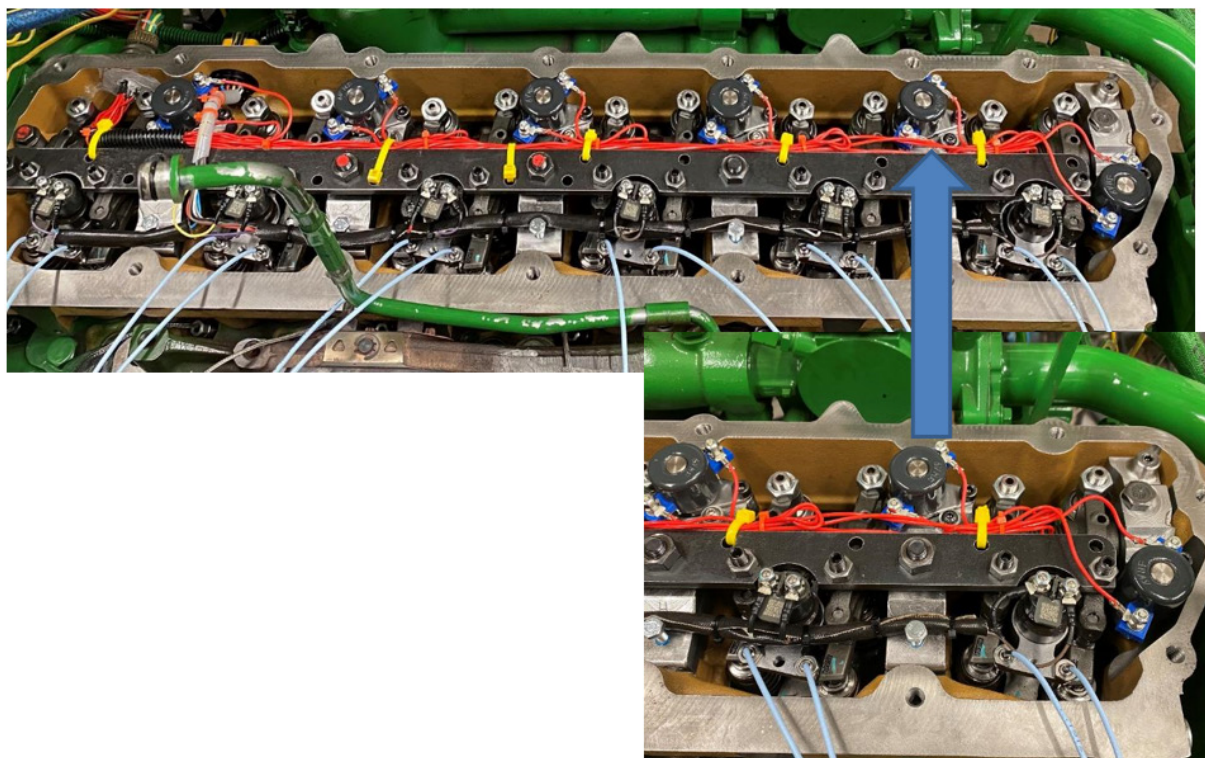


FIGURE 13. CYLINDER DEACTIVATION SYSTEM (JACOBS VEHICLE SYSTEMS)

2.5.2. *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 a lighter load. An illustration of how this concept works is given below in Figure 14. The use of dDSF can enable a wider range of more frequent CDA under transient cycles, thus enabling a larger benefit than map-based CDA. In addition, dDSF can be used to avoid Noise, Vibration, and Harshness resonances in a more dynamic fashion, thus enabling CDA to be used more readily in areas that might otherwise be limited in flexibility due to vibration limits. When DSF is referred to in this report, it refers to the combined use of CDA with the dDSF control algorithm.

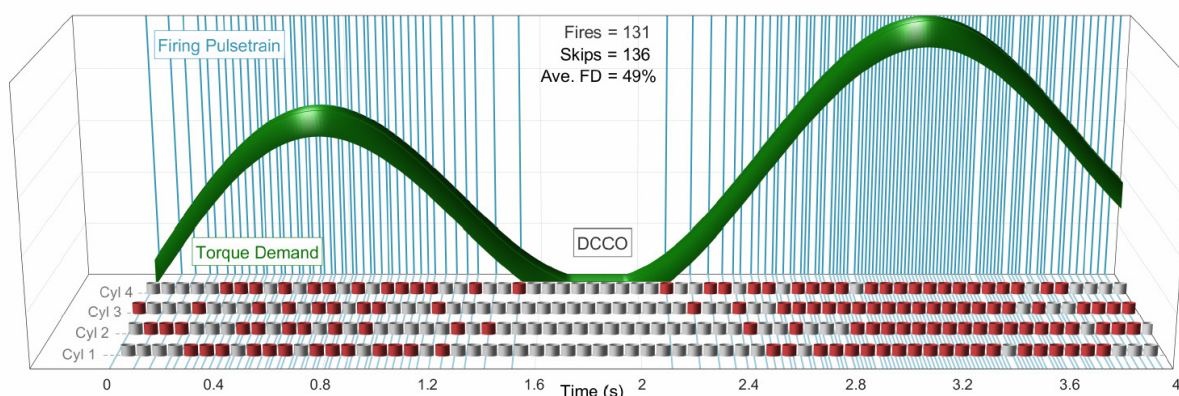


FIGURE 14. ILLUSTRATION OF DYNAMIC SKIP FIRE (FROM TULA PRESENTATION AT 9TH INTERNATIONAL ENGINE CONGRESS, BADEN-BADEN, GERMANY)

2.6 Low NO_x Controls

The basic control architecture for the Stage 3 demonstration is shown in Figure 15. The core strategy and much of the custom controls were operating from the SwRI Controller, which resided in a dSPACE MicroAutoBox II (MAB2) platform. The controller hardware itself is shown in Figure 16. 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 adjust directly.

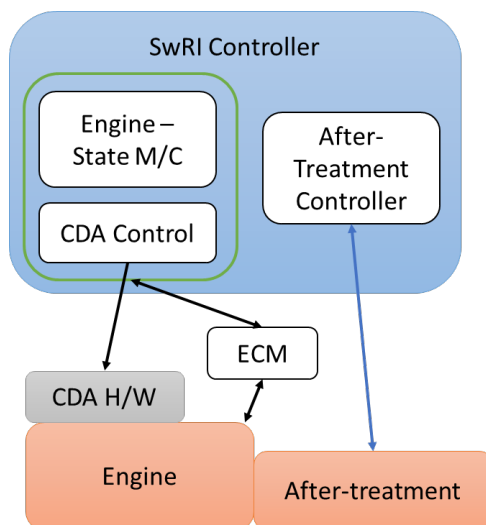


FIGURE 15. HIGH-LEVEL CONTROL STRUCTURE FOR STAGE 3 LOW NO_x DEMONSTRATION

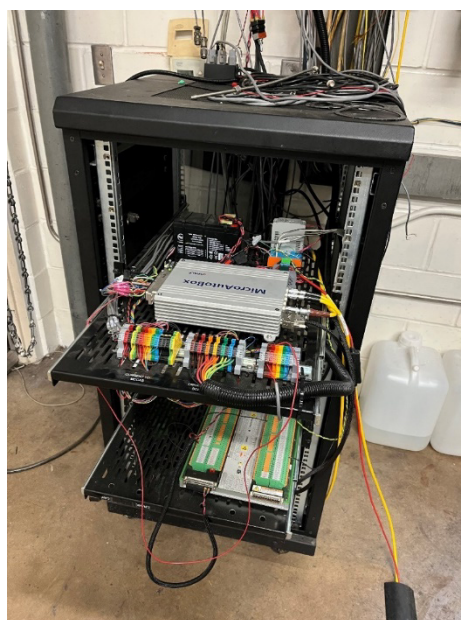


FIGURE 16. LOW NO_x INTEGRATION CONTROLLER HARDWARE PLATFORM

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 with 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 Light Off SCR

Catalyst (LO-SCR) temperature and the temperature of the first brick of the downstream SCR system (SCR1 in the diagrams) were used to drive state switching. The strategy is shown in Figure 17 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 CO₂ 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 CO₂ 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 CO₂, 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 CO₂ penalty than the TM-1 mode. The flexibility added by TM-2 was essential for optimizing CO₂ emissions in part load duty cycles.

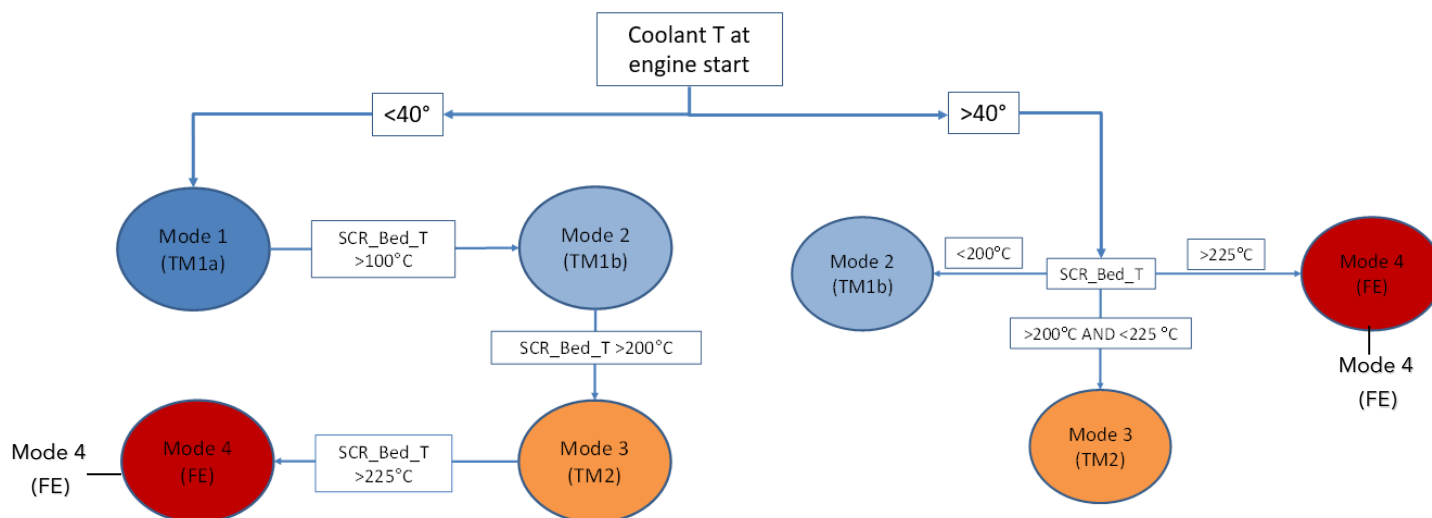


FIGURE 17. ENGINE STATE MACHINE AND OVERALL STRATEGY CONTROL DIAGRAMS

Under normal operations after engine-start and when ECT was above 40 degrees Celsius (°C), these three modes were the only active modes, and the strategy work cycle between these modes as 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 Modes TM1a in Figure 17) were enabled under the TM-1 mode to implement the 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 18 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 detailed in Section 4.

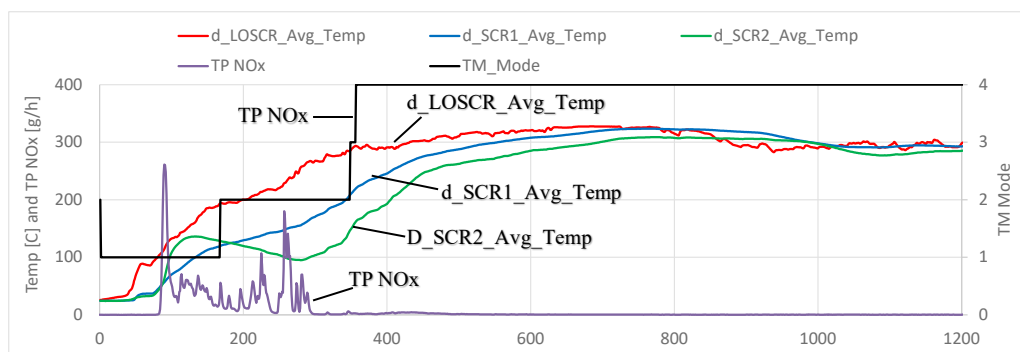


FIGURE 18. EXAMPLE OF CONTROL MODE SWITCHING DURING COLD-NRTC

Additional specialized control modes were also implemented for specific functions, such as DPF Regeneration or SCR desulfation. 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 Sections 2.6.2 through 2.6.4. Due to scope limitations, not all of 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 DEF dosing control architecture for this program was essentially the same one that was developed for the primary Stage 3 demonstration program. A high-level representation of the approach is given below in Figure 19. The DEF dosing controller is a model-based controller, wherein a lumped parameter, a physics-based model is used to build an ammonia coverage observer which acts as a virtual sensor to monitor the ammonia storage state of the catalysts. The Tier 5 controller used three such observers and sub-controllers, one for the upstream SCR volume (the Multi-Function Catalyst (MFC)), and two for the downstream SCR volumes (upstream and downstream of the mid-bed ammonia sensor). It should be noted that the overall controller incorporates several features to help balance the performance of the system across the two different catalysts (upstream and downstream), allowing for the systems to compensate for each other in an automated fashion.

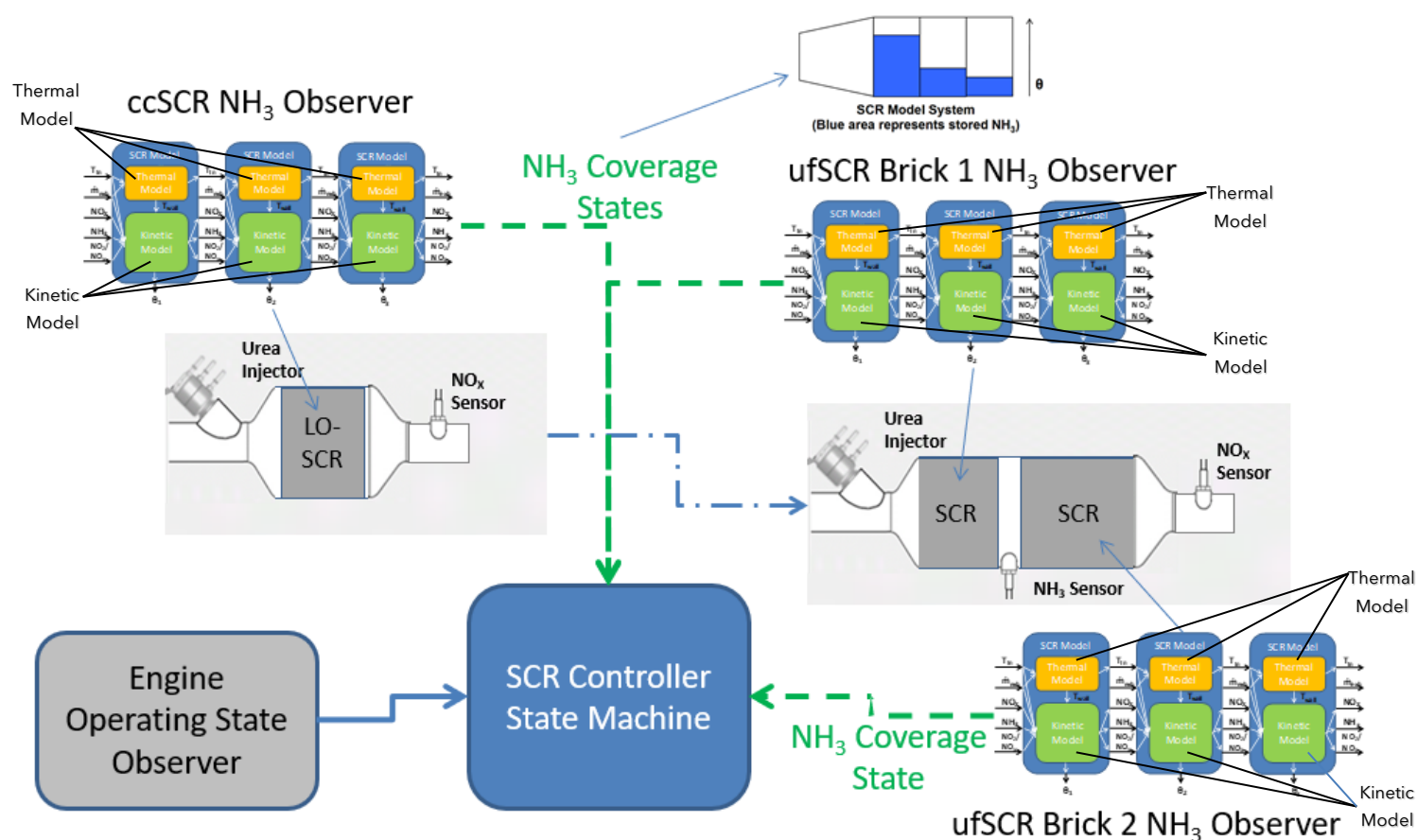


FIGURE 19. HIGH-LEVEL SCHEMATIC OF DUAL SCR DUAL DEF DOSING CONTROL ARCHITECTURE

The upstream SCR sub-controller is depicted in Figure 20, and the basic control structure is shown in Figure 21. This system was patterned from the controller used for the LO-SCR system under the on-highway Low NO_x program. As with the downstream system controller, the key calibration parameters are the coverage targets, the feed forward ammonia-to-NO_x ratio, and various system gains and thresholds.

It should be noted that the overall strategy for systems with a LO-SCR (MFC) is to target coverage at low temperatures for maximum conversion, and then to back off on dosing at higher temperatures, allowing the upstream SCR to empty of ammonia, and thus permit most of the engine-out NO_x to reach the filter to facilitate passive soot oxidation. At these higher temperatures, the larger downstream SCR takes on the majority of the effort of NO_x reduction, and the MFC is only used to target a relatively modest 20-30% NO_x conversion.

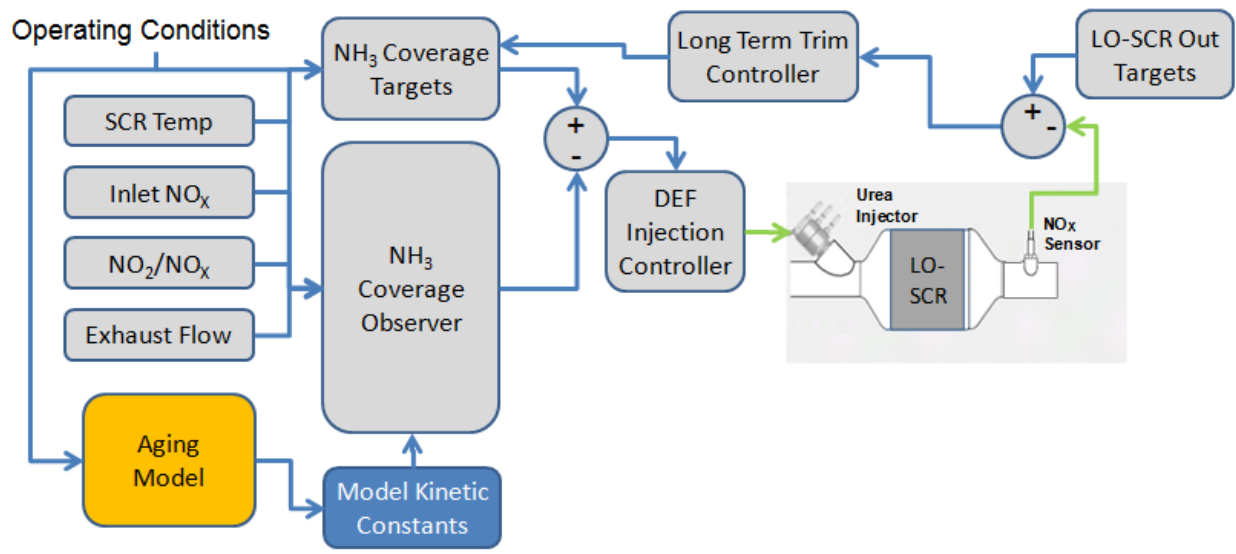


FIGURE 20. UPSTREAM (LO-SCR/MFC) DOSING CONTROLLER SCHEMATIC

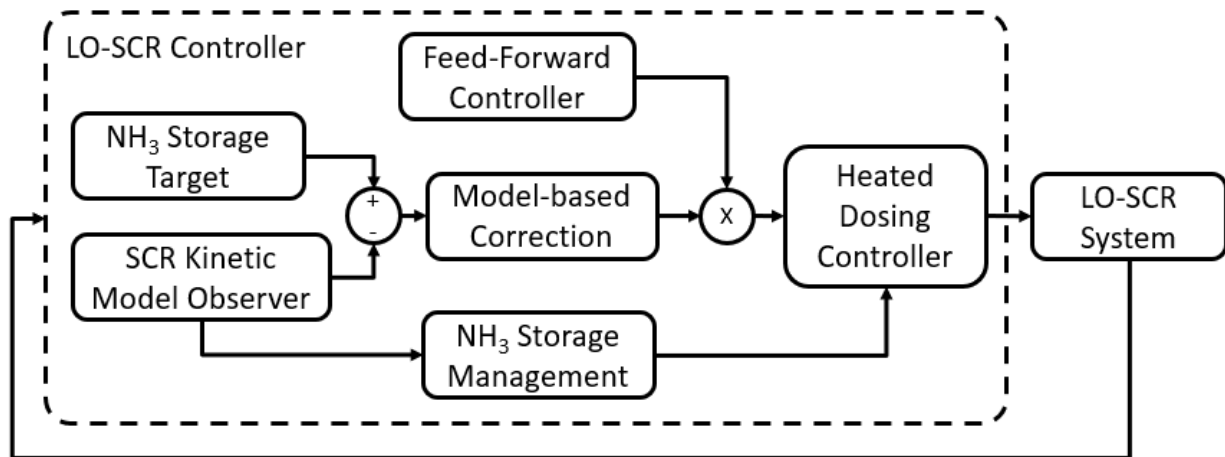


FIGURE 21. UPSTREAM SCR CONTROLLER STRUCTURE

The downstream SCR sub-controller is depicted in Figure 22, and the basic control structure is shown in Figure 23. This system was patterned from the controller used for the downstream SCR system under the on-highway Low NO_x program.

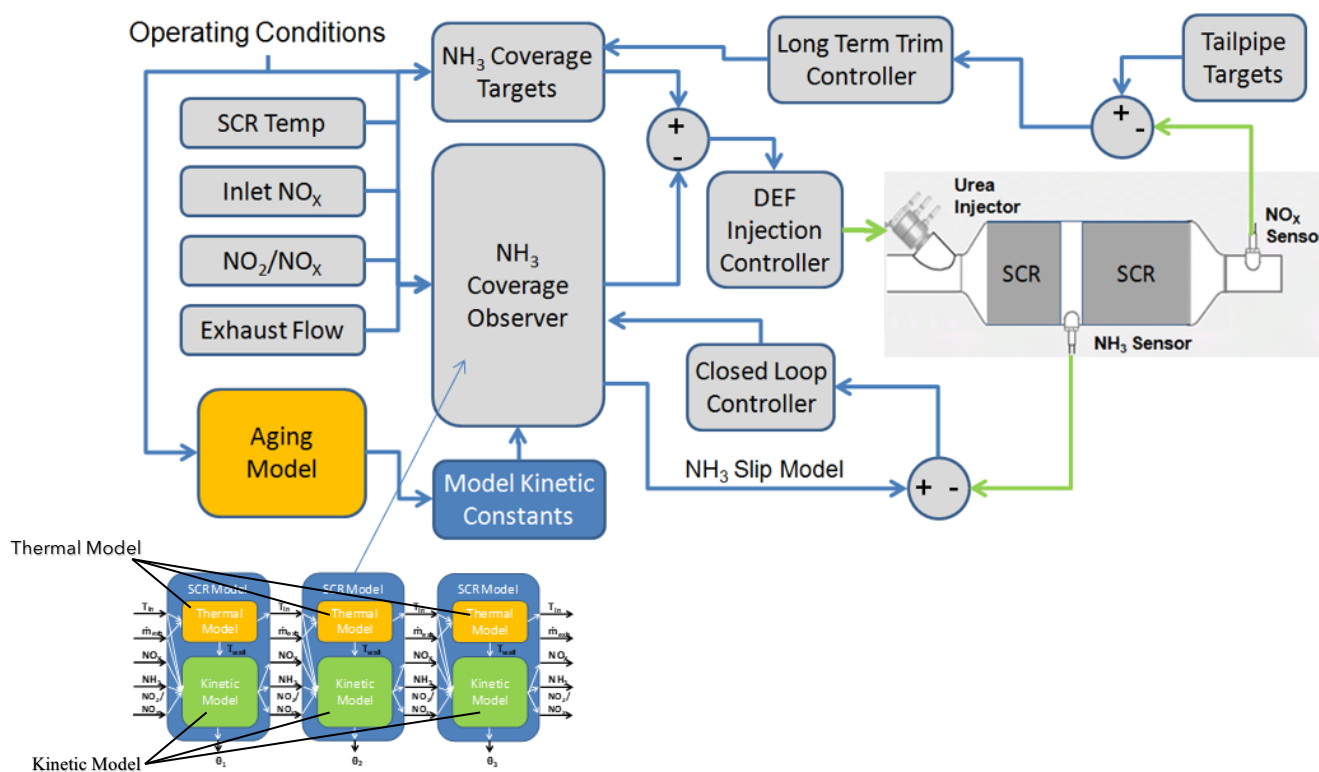


FIGURE 22. DOWNSTREAM SCR DOSING CONTROLLER SCHEMATIC

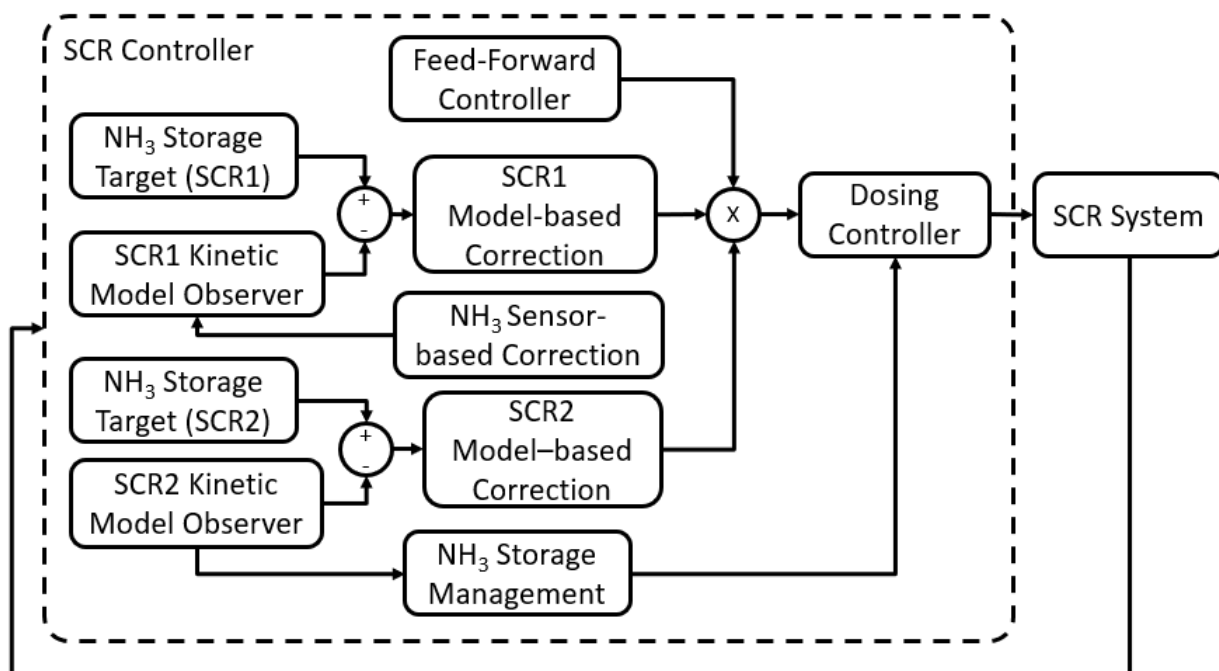


FIGURE 23. DOWNSTREAM SCR CONTROLLER STRUCTURE

As shown in Figure 23, the downstream command is the sum of corrections for both the first downstream SCR bed (SCR1), which is before the NH₃ sensor, and the

second downstream 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 downstream catalyst controller also contains the same deposit avoidance limiting of maximum dosing and accelerated dosing features as the upstream controller.

An additional feature was a high-speed feedback element for model state correction, 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 control 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 downstream SCR catalyst 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 downstream 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 sensor 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 30 parts per million) 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 22 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, 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." The detection of the rapid concentration rise of this "wave" does not shift a practical amount in time regardless of the accuracy of the NH_3 sensor gain. On the timescale of the concentration rise, detecting at 10% or 50% of the rise both yields a practical and useful signal for shimming the dosing schedule. This allows the feedback algorithm to correct storage over a timescale of seconds to minutes, and the more accurate storage prediction allows the controller to correct catalyst behavior better.

2.6.3. 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 two (or three) 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 the 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 useful 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. Although this is useful under many field situations, for the off-road duty cycles, the NRTC poses a particular challenge in that it operates at temperatures that do not readily allow for recovery of ammonia storage before engine shut down. This poses a challenge different from the on-highway cycles, which will be discussed later in Section 4 of the report. 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. With regard to the heated dosing system, it should be noted that there are several heat-enabled options for low temperature dosing, including dosing onto a small heater or heated mixer, in addition to the option chosen for this program, which involved direct heating of the DEF fluid under pressure.

2.6.4. Aftertreatment Control System Updates Following Tier 5 Demonstration Tests

The control architecture used for this program was essentially the same as the one that was used for the original Tier 5 demonstration work at the end of the previous work under CARB Contract 20MSC005. However, there was a modification that was made as part of the alternate packaging work that was conducted on behalf of EMA. It was found that the alternate package caused a large separation between the upstream and downstream SCR temperatures, and that the original controls were not robust enough to handle this difference properly. An example of the temperature differences between the packages is shown in Figure 24. The result of this was that the system backed off on the MFC too early in some cases, before the downstream SCR was warm enough to handle the load.

There was an existing function called “Balance Mode” in the system that was designed to help compensate for temporary downstream system shortfalls, but it had been calibrated to trigger based on the lack of ammonia storage in the Base system. By adding an additional trigger to this existing function that utilizes low downstream system temperature, the controls were modified to be much more robust to this issue. As it turned out, this change was also useful for addressing certain Child rating performance issues on the LLC that were observed in the original Tier 5 demonstration testing.

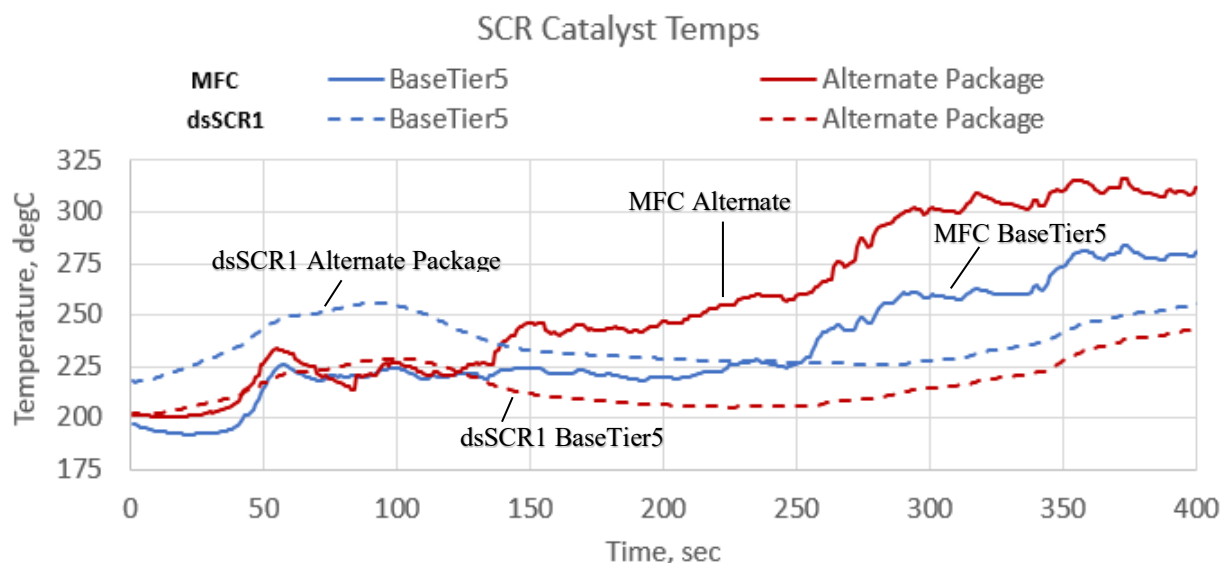


FIGURE 24. COMPARISON OF SCR CATALYST TEMPERATURES BETWEEN ALTERNATE AND BASE TIER 5 AFTERTREATMENT PACKAGING CONFIGURATIONS

As a result of these improvements, the updated controls architecture was retained for all subsequent work, and it was utilized for the field cycle testing as well. The emission performance results for this controls update are documented in Section 4.

2.7 Field Cycle Analysis Methodology

Although it is possible to look at the overall brake-specific NO_x (BSNO_x) emissions on any given field cycle, this result is not meaningful in the context of how in-use data will be examined. Instead, the data from the field cycles was analyzed using a binned Moving Average Window approach that was first introduced for on-highway in-use testing in the CARB Low NO_x Omnibus rule and United States Environmental Protection Agency 2027 Heavy-duty Low NO_x rule. Under this approach, data is analyzed using a fixed width 300-second window, which is advanced through a continuous data set one second at a time. The resulting windows are then sorted into bins using an engine load metric. A final emission result is then determined for each bin by aggregating the accumulated window results in that bin. Both 2-bin and 3-bin versions of this method have been discussed at various times.

In the case of off-road emissions, the final form of this methodology is not yet known, however CARB has proposed a 3B-MAW approach in 2024. In this report data

is analyzed using both a 3-bin and a 2-bin approach. Each bin is intended to be associated with a particular cycle and standard for off-road engines. The binning parameters and associated cycle standards for the 3B-MAW method are given in Table 4.

TABLE 4. 3B-MAW BIN PARAMETERS AND STANDARDS FOR OFF-ROAD IN-USE TESTING

In-Use Bins	% Rated Power	In-Use PEMS Thresholds
Screening Bin A	$\leq 8\%$	CF x Idle standard + $m_{\text{PEMS Accuracy}}$
Screening Bin B	$> 8\%$ to $\leq 25\%$	CF x OR-LLC standard + $m_{\text{PEMS Accuracy}}$ + m_{interim}
Screening Bin C	$> 25\%$	CF x NRTC standard + $m_{\text{PEMS Accuracy}}$ + m_{interim}

The 2023-2024 off-road in-use proposal released by CARB uses engine speed and torque, as broadcast on the CAN bus via J1939 to determine engine power. The average power over a given 300-second window is divided by the engine rated power to give the % Rated Power for bin sorting. However, broadcast torque is not always accurate. An alternative approach for bin sorting is to use normalized CO₂ mass as a load metric, where the CO₂ mass over the 300-second window is divided by the CO₂ mass emitted for a window that ran at maximum power. This alternate approach is the one that will be utilized for the on-highway in-use testing program. Both sets of calculations are utilized for this report. For torque-based calculations in this report, Laboratory measured torque was used because a properly calibrated broadcast torque was not available on this engine for the two ratings.

When CO₂ is used, it is necessary to use a brake-specific CO₂ (BSCO₂) emission value to calculate Bin B and C emissions into brake-specific units. For CO₂-based calculations in this report, the BSCO₂ for the NRTC is used for this purpose, similar to how the BSCO₂ for the Federal Test Procedure (FTP) is used for on-highway engines. The values used for both maximum power and BSCO₂ for the two engine ratings tested in this program are given in Table 5. The CO₂ mass denominator used for normalized CO₂ binning is the product of these two values scaled to the 300-second window duration.

TABLE 5. VALUES FOR CO₂-BASED B-MAW CALCULATIONS

Rating	Maximum Power	NRTC BSCO ₂
	kW	g/kW-hr
Nominal	187	700
Child	126	770

For CO₂-based calculations, the laboratory measured CO₂ emissions were used. However, on selected tests, a broadcast fuel rate is also made available. When that signal is available it is also possible to use the fuel rate to determine a CO₂ mass rate for purposes of xB-MAW calculations, using an assumed fuel weight fraction of carbon. If CO₂-based calculations are ultimately chosen, this is the approach that will need to be used for sensor-based measurements during the screening portion of the off-road in-use program. When the fuel rate broadcast is available, the fuel-based CO₂ values are also determined to provide additional information about that approach.

As noted earlier, the default approach was to use a 3-bin sorting metric. However, SwRI also examined the use of a 2-bin metric, similar to the on-highway approach. In that case, Bins B and C are combined into a single bin which is used for all windows above 8% average power. For the combined Bin B/C threshold, a “placeholder” threshold value was calculated weighting the Bin B threshold at 33% and the Bin C threshold at 67%. This weighting has some basis in that the off-road LLC development analysis indicated that 27% of the operating windows in the database fell into the Low Load region of operation. For the purposes of this study the weight at 33% resulted in a more “rounded” threshold of 70 milligrams per kilowatt-hour (mg/kW-hr) at the 1.5 conformity factor (CF).

3.0 FIELD CYCLE DEVELOPMENT

This section of the report details the development of the field cycles that were used in this program to evaluate the performance of the Tier 5 demonstration engine. As noted earlier, these field cycles were based on real-world application data from various machine applications. The data was normalized into a format compatible with cycle calculations in 40 CFR Part 1065 to allow them to be run in an engine test cell.

3.1 Input Data Sets for Field Cycle Development

The development of the field cycles was based on the same data set of in-use operation that was leveraged for the development of the off-road LLC. The data came primarily from two large field activity data gathering programs that CARB ran over the 2 years preceding the start of the off-road LLC development. One such program focused on construction machinery under CARB Contract 17RD013, while the other program focused on agricultural equipment under CARB Contract 19RD002. CARB also obtained a significant body of data from a third program which was focused on off-road yard tractors (though the number of engines in that third study was small, necessitating a special data treatment to avoid over-weighting those results). Overall, these CARB data sets contained operating data from 110 different engines, encompassing a wide variety of applications across 24655 hours of equipment operation.

This CARB data set was then augmented by contributions from many of the off-road engine and equipment manufacturers which actively participated as part of the Steering Committee. Data was received from 10 different manufacturers, comprising an additional 130 engines and 932 hours of operation (many of these data sets were much shorter individual runs than the longitudinal data collection in the CARB contracted data sets). These additional data sets proved valuable in further broadening the reach of the input data set in terms of variety of applications and by providing opportunity for manufacturers to further inform the representativeness of the aggregate data set underpinning this analysis work.

Figure 25 shows a breakdown of applications represented in the data set by machine population. Roughly half of the data came from agricultural tractors, which is consistent with the overall fraction of such tractors in the population of off-road machines in California, as described in the market survey data from the Stage 1 report (Contract 18RD006). Figure 26 shows a histogram of the distribution of engine power levels in the data set, with much of the population falling between 56 kW and 450 kW.

The breadth of the data set helps to ensure the representative nature of the resulting cycle.

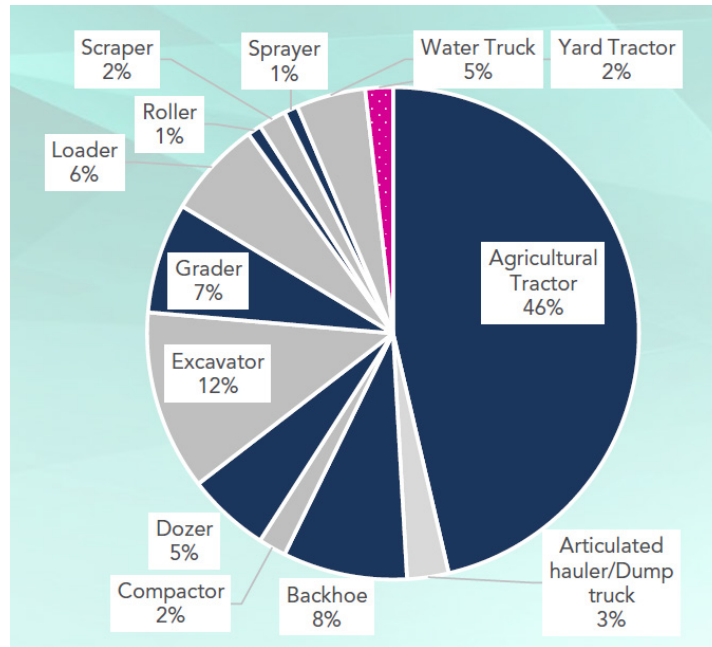


FIGURE 25. APPLICATION BREAKDOWN IN THE LLC DEVELOPMENT INPUT DATA SET

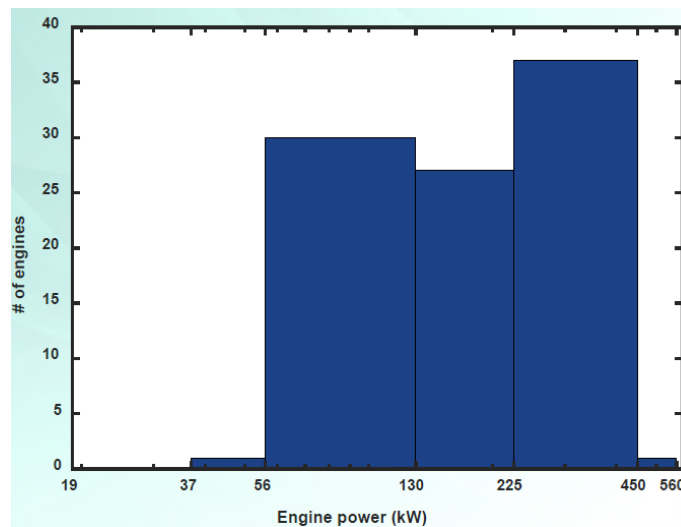


FIGURE 26. HISTOGRAM OF ENGINE POWER LEVELS IN THE LLC DEVELOPMENT INPUT DATA SET

3.2 Field Cycle Selection

To support the Tier 5 off-road in-use testing program rulemaking effort, CARB staff developed seven up-to-8-hour field cycles from real-world activity data. CARB staff selected test cycles based on criteria such as equipment type, power category, cycle average load, daily total run time, idle operation time, window numbers for each

bin, etc. CARB staff also ensured there was a diversity of engine manufacturers represented in the data sets. Initially, CARB staff selected 14 different application data sets as potential candidates for field cycle development. Working with SwRI, this initial data set was narrowed to the final seven cycles given below. All cycles included a cold-start, and some cycles include engine shut down and restart after a period of engine-off time.

Descriptive characteristics for the final seven cycles are listed in Table 6 below. These cycles show a diverse range of equipment applications (Agricultural, Construction, Yard tractors), engine displacement (4.5 L to 15 L), operational durations (4.5 hours to 14.6 hours), number of windows for each bin, and engine load profiles (11.1% to 47%). All the cycles meet the minimum window requirement of 10,000 for Bin B and C combined, except for cycle 12. More than half of the cycles meet the minimum window requirement of 2400 for Bin A. For the cycles that did not meet the minimum number of windows requirements for Bin A, an additional 30 minutes of idle was intentionally added at the end of the testing. The comprehensive approach ensures robust evaluation of engine emission performance under a variety of real-world conditions. It should be noted that the final number of windows in each bin varied depending on the engine rating tested, the use of DSF, and the cycle.

TABLE 6. FIELD CYCLE DESCRIPTIVE DETAILS

Cycle Name	Applications	Average Load (%)	Engine-On Time (s)	Engine-On Time (hr)	Projected Number of Windows by Bin		
					Bin A	Bin B	Bin C
Cycle 1	Construction and Mining – Backhoes	17.9	26,803	7.4	6962	12136	8004
Cycle 4	Agricultural Tractor	47	34,276	9.5	4365	5596	24016
Cycle 7	Agricultural Tractor	39.6	52,695	14.6	6380	5987	39101
Cycle 9	Construction and Mining – Excavators	32.2	27,810	7.7	1842	10213	15596
Cycle 11	Construction and Mining – Excavators	32	27,935	7.8	2018	3254	22364

Cycle Name	Applications	Average Load (%)	Engine-On Time (s)	Engine-On Time (hr)	Projected Number of Windows by Bin		
					Bin A	Bin B	Bin C
Cycle 12	Construction and Mining – Off-Road Yard Tractors	11.1	16,205	4.5	6518	8179	1209
Cycle 14	Construction and Mining – Off-Road Terminal Tractors	15	17,207	4.8	2300	1416 7	441

3.3 Field Cycle Translation for Laboratory Usage

The field cycles initially came in the form of CAN recorded data for speed and load for the individual machines that were logged. However, these could not be used directly in the test cell given that the data came from a wide variety of engines. Therefore, it was necessary to translate these data sets into normalized engine cycles that could be run on any engine. The process for doing this was similar to what was used during the development of the off-road LLC for the field profiles that were used as building blocks for the final cycle.

For each field data set, the appropriate engine torque curve was used to normalize the data. Other parameters such as fuel rate and exhaust mass flow rate were also used to help in the translation process, particularly for the identification of low idle and motoring segments of operation. Where necessary, some idle was inserted at the start and end of cycles to facilitate laboratory operations. Some cycle cleanup was also performed to prevent excessive speed transitions that would not be supported by the test cell, or to smooth any glitches in the field recorded data sets.

An example of input and output of this translation process is given in Figure 27 for the initial recorded data input, and in Figure 28 for the final normalized output cycle. Note that this cycle did feature an engine shutdown near the 21,000-second mark, and this is flagged in Figure 28 via the Engine On variable shown in orange.

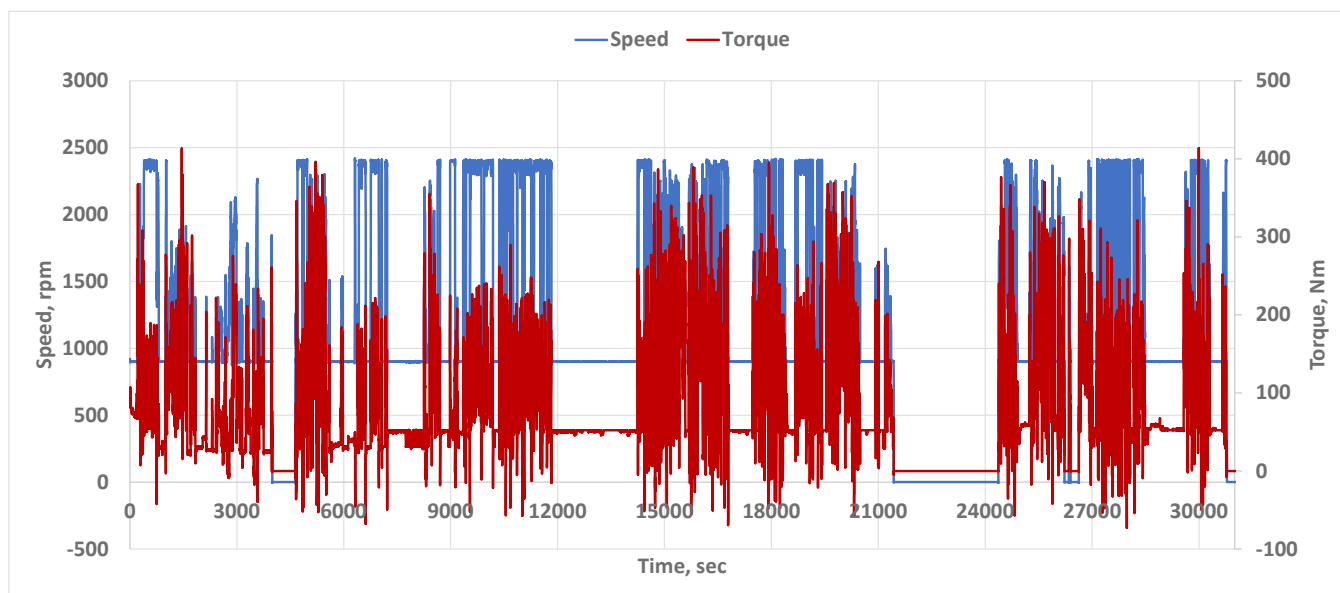


FIGURE 27. INITIAL RECORDED FIELD CYCLE DATA FOR FIELD CYCLE 01 (BACKHOE)

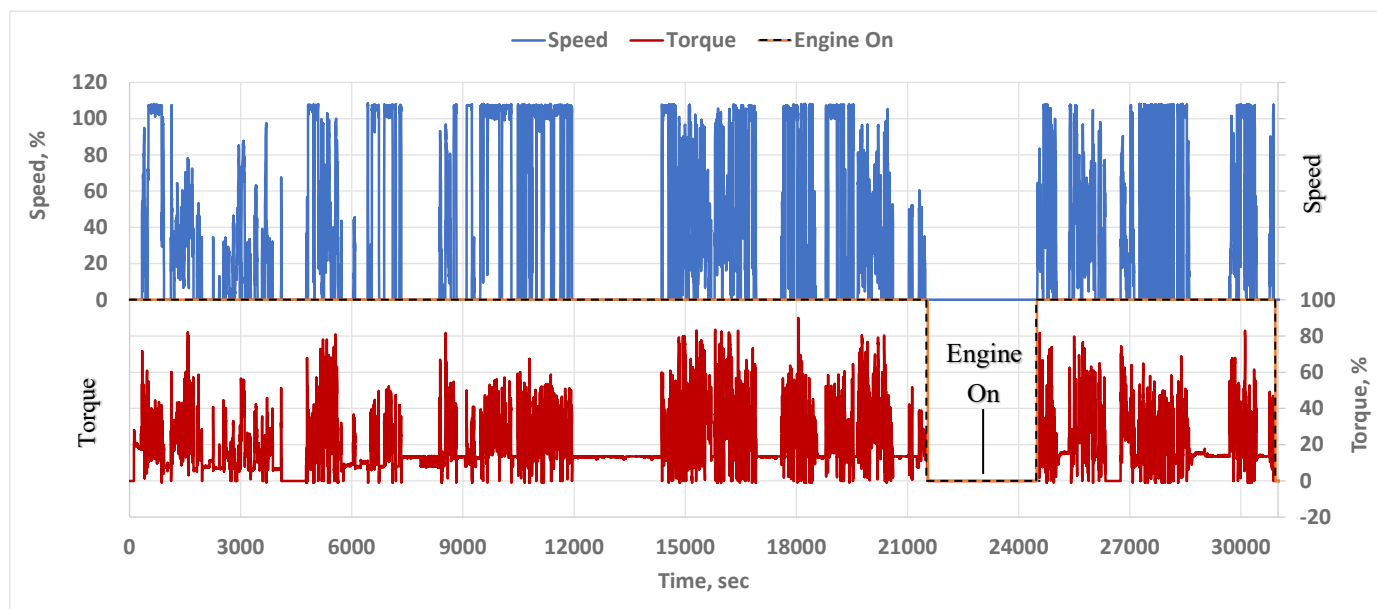


FIGURE 28. FINAL NORMALIZED FIELD CYCLE FOR LAB USAGE FOR FIELD CYCLE 01 (BACKHOE)

The final seven cycles are depicted in Figure 29 in a normalized format. As can be seen in the figure, these cycles represent a diverse set of different operation profiles from a variety of applications. Both constant speed and variable speed operating profiles are seen, as well as a wide variety of load profiles for both high load and light load operations. More detail on the individual cycles is given in Appendix A.

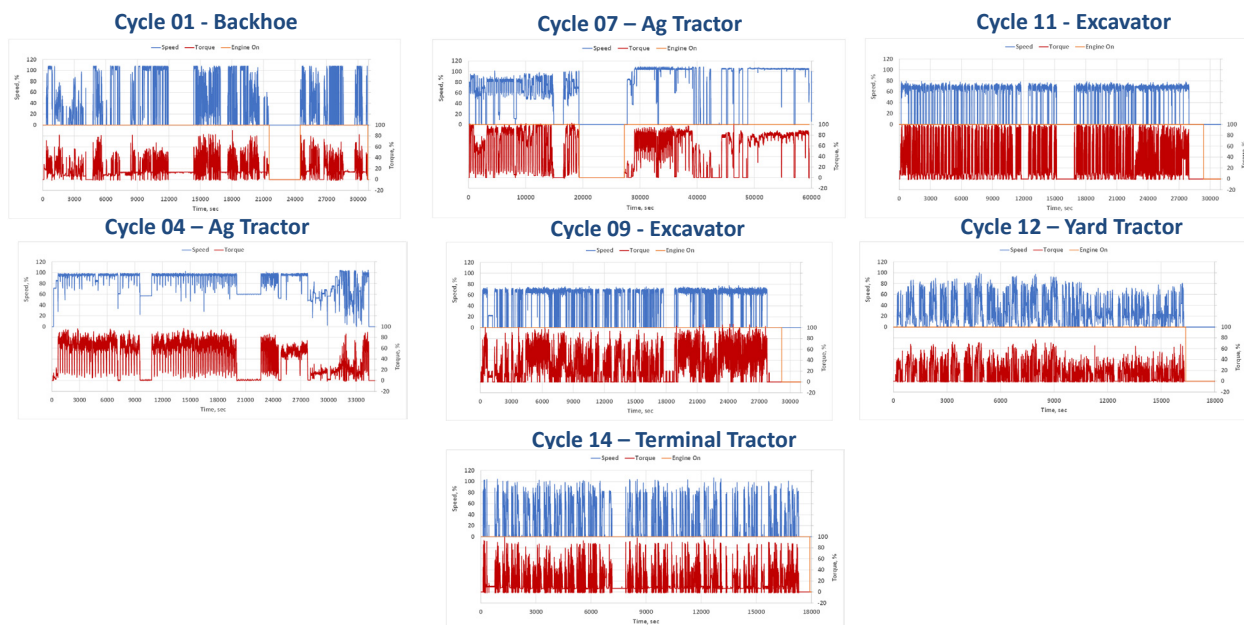


FIGURE 29. NORMALIZED FIELD CYCLES

4.0 RESULTS AND DISCUSSION

This section of the report details the emission test results for the Tier 5 demonstration engine on the various field cycles. LLC cycle results are also shown, as well as a comparison to regulatory cycle results where appropriate. Analysis and interpretation of these results are also given in this section, including a comparison of results from different in-use data calculation methodologies.

4.1 Previous Program Results on Regulatory Cycles

The final demonstrated NO_x emission levels for the Tier 5 Low NO_x demonstration engine are given in Figure 30 for all the key program test cycles, both with and without the use of DSF. These compliance values are the 8000-hr DAAAC-aged (Diesel Aftertreatment Accelerated Aging Cycle) emission results with Upward Adjustment Factor (UAF) for infrequent regeneration added in. These are the values that would be compared to the standards, and the proposed Tier 5 standards for engines above 56 kW are also shown in the table for reference. For all test cycles it is apparent that a margin of 50% or more is available to the proposed standard levels, with margins of at least 20 mg/kW-hr present on all cycles. The values shown are for a Closed Crankcase Ventilation system.

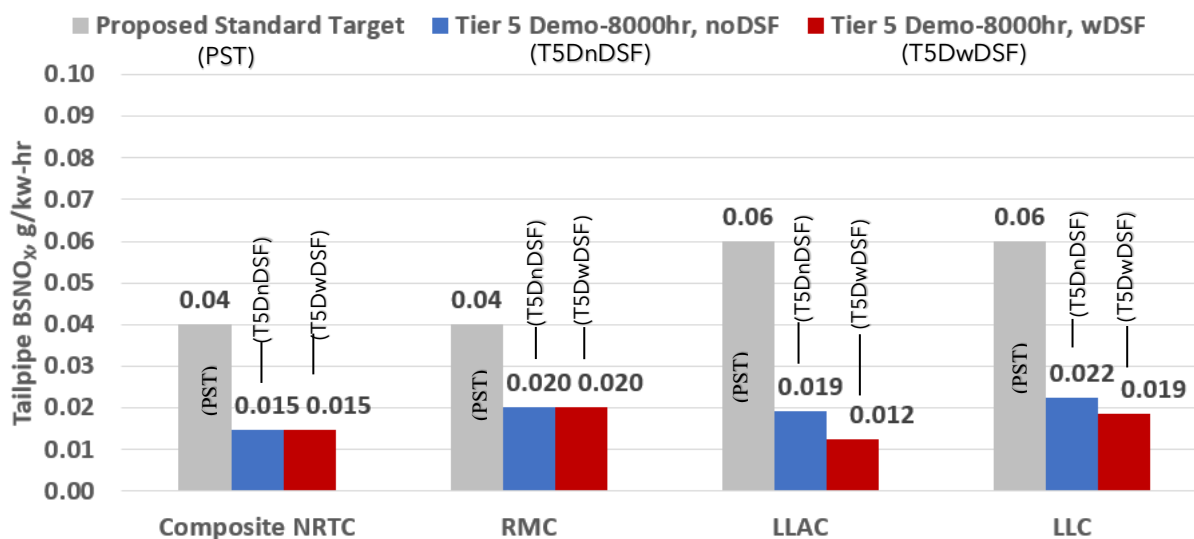


FIGURE 30. TAILPIPE NO_x COMPLIANCE VALUES FOR TIER 5 LOW NO_x DEMONSTRATION ENGINE ON THE NOMINAL (187 KW) RATING

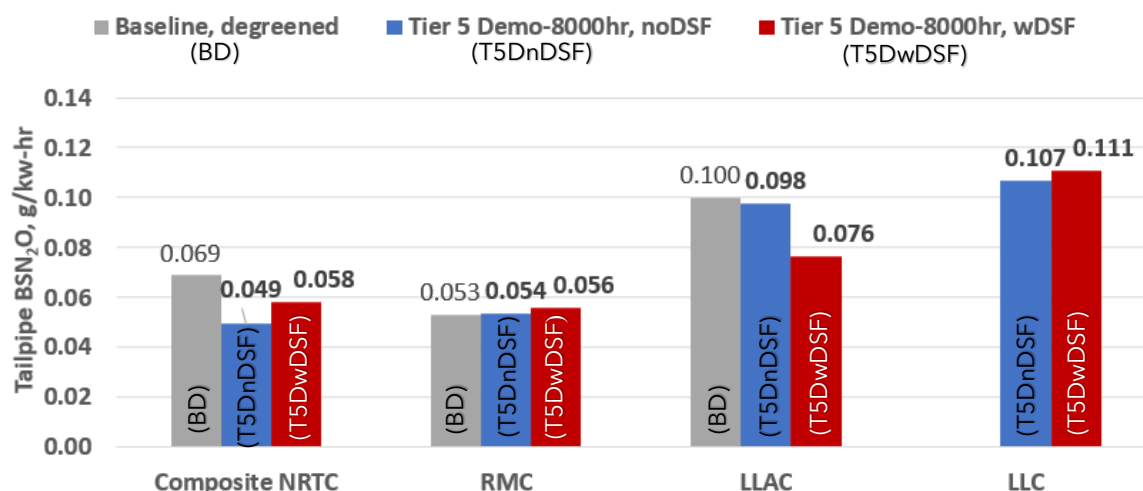


FIGURE 31. SUMMARY OF TAILPIPE BSN₂O FOR LOW NO_x PACKAGES COMPARED TO BASELINE

As with many off-road engines, the 6.8L 6068 supports a wide range of different torque curves and rated power options, as depicted in Figure 32. The primary demonstration effort was carried out using a 187 kW rating, which is termed as the “Nominal” rating for this program. However, testing was also conducted using the low power “Child” rating of 126 kW.

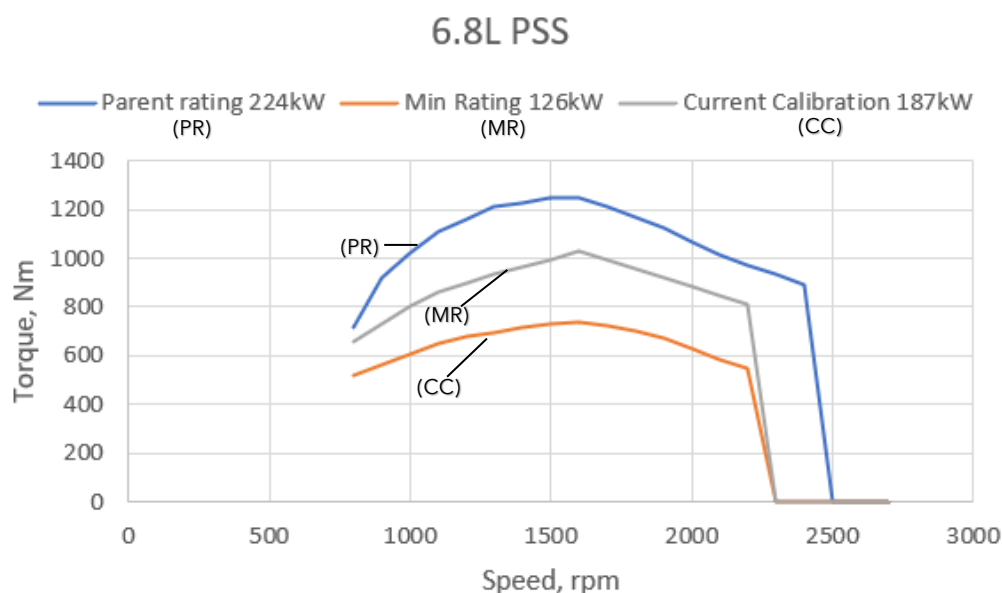


FIGURE 32. RANGE OF AVAILABLE CHILD RATINGS FOR THE JOHN DEERE 6068 DEMONSTRATION ENGINE FAMILY

The results of the initial evaluation of the Child rating are shown in Figure 33 as the hollow bars, compared to the Nominal rating results, which are shown in the solid bars. For the most part, the results are similar, except for on the LLC where significant increases in tailpipe NO_x were observed. Unfortunately, the scope of the original

demonstration did not allow for a robust examination of ways to address this. However, during subsequent efforts that were conducted on behalf of EMA to examine the alternate package arrangement, a controls strategy improvement was identified to address temperature issues related to the separation of the AT system parts in that alternate package. That fix involved improvements to the part of the dosing system control that seeks to balance the upstream and downstream catalyst performance, as discussed in Section 2.6.5. This improvement, though initially designed to make the system more robust to different packaging architectures, turned out to also address the issues observed on the LLC. The performance of the updated controller is shown

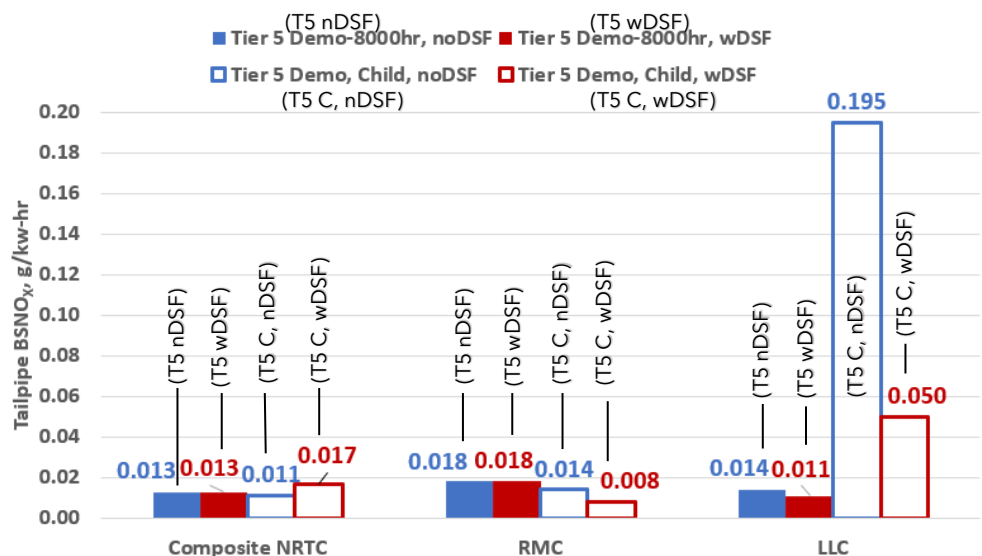
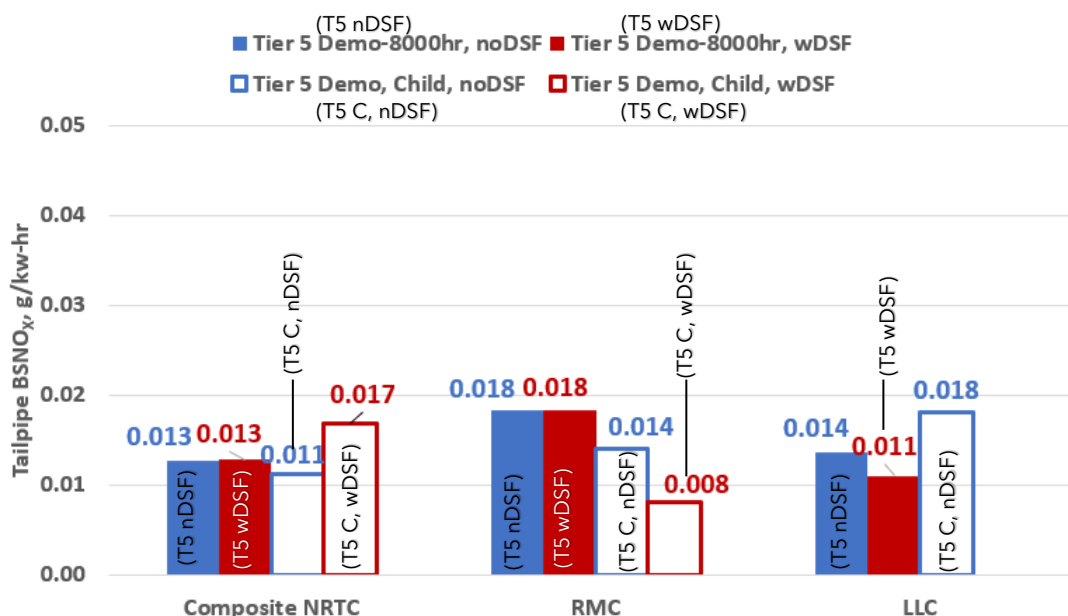


FIGURE 33. TAILPIPE BSNO_x ON REGULATORY CYCLES FOR BOTH ENGINE RATINGS – ORIGINAL TIER 5 CONTROLS



in Figure 34. A significant improvement is seen in tailpipe NO_x on the LLC, from nearly 0.2 g/kW-hr to below 0.02 g/kW-hr. This change also likely made the system more robust to various in-use duty cycles.

4.2 Initial Field Cycle Test Results

The initial evaluations of the various field cycles were carried out using the Base Tier 5 AT package. In addition, these runs were made with DSF enabled. Note that each of these test runs required a full extended shift-day to complete. To keep the scope of the program within budget limits, each cycle was evaluated on the engine rating that it was considered to be the most challenging. The list of ratings used for each cycle during the initial evaluations is given in table 1. In general, cycles with higher average power were evaluated using the 187 kW rating to push performance on high engine-out NO_x conditions. Cycles with lower average power were evaluated using the 126 kW to push performance and thermal management under lower temperature conditions. Cycle 01 featured a combination of both types of operations and was evaluated at both ratings. It should be noted that SwRI ran all of these cycles using an idle load of 78 Nm, which is 3.5% of the Nominal rating maximum power, regardless of which rating was being run. This is a change from previous practice, and it is discussed in more detail in Section 4.3 of this report. Unless otherwise noted, all LLC and Field Cycle tests use this same idle load.

Table 7. Ratings Evaluated for the Various Field Cycles

Field Cycle	Rating
Cycle 01	126 kW, 187 kW
Cycle 04	187 kW
Cycle 07	187 kW
Cycle 09	126 kW
Cycle 11	187 kW
Cycle 12	126 kW
Cycle 14	126 kW

Table 8 shows a summary of NO_x results for both 3-bin and 2-bin MAW analysis of the results from these initial field cycle tests, along with the proposed NO_x thresholds for comparison (not including any Portable Emissions Measurement System (PEMS) or interim compliance margins). The table also shows the number of windows within each bin, along with the currently proposed requirements. These results are generated using CO₂-based calculations. The table shows values for Bins A, B, and C, as well as for a combined Bin B/C which would be for a 2-bin analysis. Thresholds are shown using conformity factors of 1.5 and 2.0. For the Bin B/C threshold a “placeholder” threshold value was calculated weighting the Bin B threshold at 33% and the Bin C threshold at 67%. This weighting has some basis in that the off-road LLC development analysis indicated that 27% of the operating windows in the database fell into the Low Load region of operation. For the purposes of this study the weight at 33% resulted in a more “rounded” threshold of 70 mg/kW-hr at the 1.5 CF.

Figure 35 shows a summary of 3B-MAW results for the seven field cycles, with Cycle 01 run twice, once on each rating. For each bin, the relevant potential NO_x standard is shown using a CF of 1.5 and 2.0. Note that there is no Bin C value for Cycle 14 because there are so few windows in Bin C (less than 300) that the value is not meaningful and very noisy. Bin A (idle) emissions for the Tier 5 engine are well below 1 gram per hour (g/hr) in all cases, which is far below the potential standard of 15 g/hr (assuming a CF of 1.5). For Bin B, values ranged from 10 to 53 mg/kW-hr, leaving roughly a 40% margin to the potential standard (not including any PEMS or interim compliance margins). Bin 2 emission values were lowest for Cycles 09 and 11, from the two excavators which featured the lowest amount of Bin A and idle operation, as well as large amounts of constant speed relatively high load operation. For Bin C, values ranged from 11 to 24 mg/kW-hr, more than 50% below the potential standard.

Table 8. SUMMARY OF XB-MAW RESULTS FOR INITIAL FIELD CYCLE TESTING

Test Run No	Cycle-Rating	Bin A		Bin B		Bin C		Bin B/C	N ₂ O, g/kW-hr
		n ^{***}	NO _x , g/hr ^{*****}	n	NO _x , g/kW-hr	n ^{****}	NO _x , g/kW-hr	NO _x , g/kW-hr	
	Thresholds at CF 1.5	min 2,400	15*	B+C min 10,000	0.090	B+C min 10,000	0.060	0.070**	
	Thresholds at CF 2.0		20*		0.120		0.080	0.097**	
2871	1 - 187 kW	7579	0.0 (0.02)	13380	0.027	6429	0.012	0.020	0.328
2866	1 - 126 kW	6754	0.0 (-0.02)	12187	0.033	8447	0.022	0.027	0.493
2845	4 - 187 kW	3661	0.0 (-0.03)	5763	0.038	24698	0.018	0.019	0.045
2885	7 - 187 kW	6501	0.7	4166	0.053	30846	0.024	0.025	0.071
2874	9 - 126 kW	2910	0.1	13477	0.010	12506	0.016	0.015	0.051
2848	11 - 187 kW	3111	0.01 (0.006)	3624	0.011	22328	0.017	0.017	0.067
2861	12 - 126 kW	<u>214</u>	0.0 (-0.07)	14323	0.046	1544	0.011	0.039	0.225
2857	14 - 126 kW	<u>2013</u>	0.4	15347	0.027	263	0.200	0.032	0.218

* Calculated Idle Standard for this engine at 187 kW is 10 g/hr

** Bin B/C possible threshold based on 33% LLC and 67% NRTC weighting

*** Underlined values are below 2,400 minimum requirement

**** Bolded values are a very low number of windows for Bin C quantification

***** Values in parenthesis are as measured, note negative measured values set to zero as specified

Figure 36 shows a similar comparison but for a 2-bin Moving Average Window (2B-MAW) analysis result. Note that in this case there are good values for Bin B (B/C) in all cases because the number of windows in that combined bin always exceeds 10,000. Bin A results remain the same as before. However, the Bin B/C results range from 15 to 39 mg/kW-hr, showing at least a 44% margin with the projected “placeholder” threshold of 0.07 g/kW-hr.

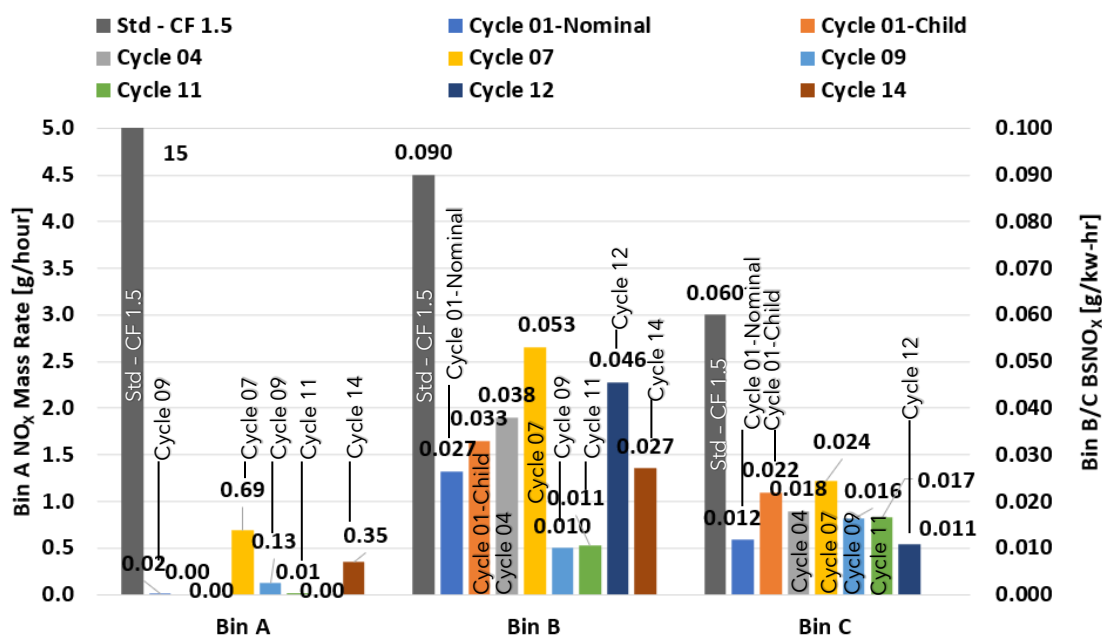


FIGURE 35. 2B-MAW RESULTS FOR INITIAL FIELD CYCLE TESTING WITH DSF ACTIVE

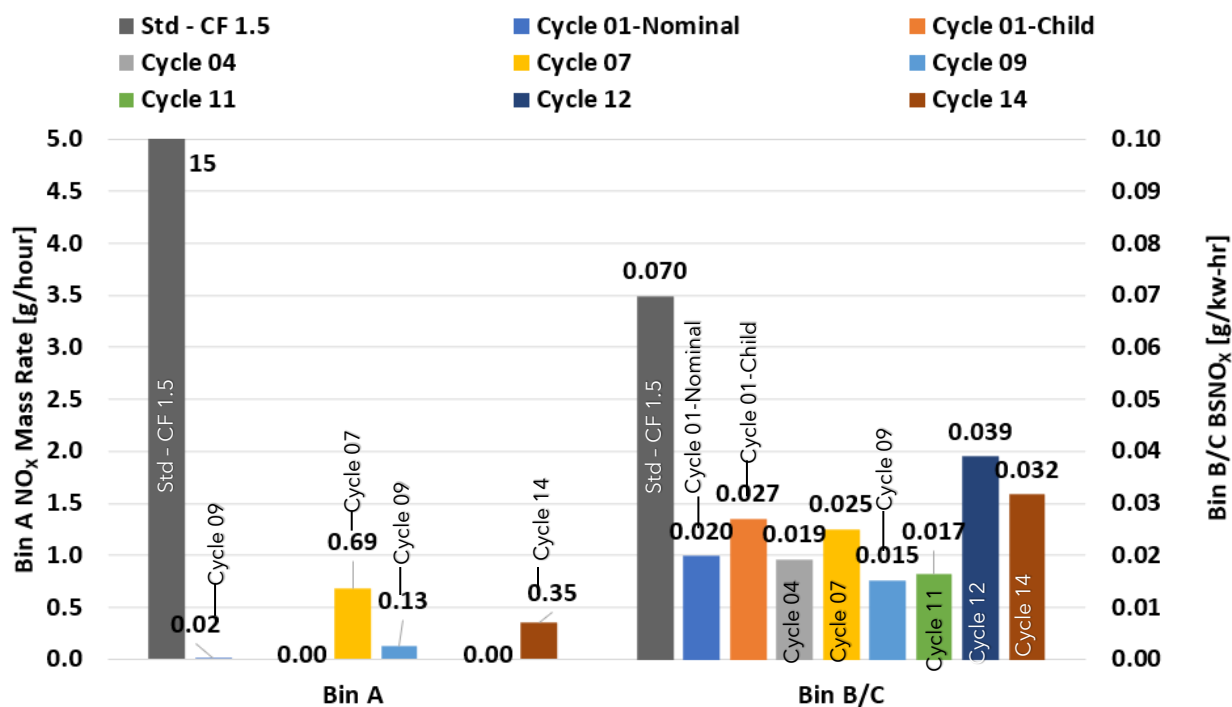


FIGURE 36. 3B-MAW RESULTS FOR INITIAL FIELD CYCLE TESTING WITH DSF ACTIVE

It is worth noting that most of the cycles which show high Bin B results for a 3B-MAW analysis also stood out as higher in Bin B of the 2B-MAW. Only in the case of Cycle 07 did this not occur, but Cycle 07 only had 4166 windows in 3-Bin B, which is above the minimum threshold of 2400 windows, but still leaves room to be dominated by the relative part load cold-start of that particular duty cycle. Therefore, it generally appears that the 2B-MAW metric should be able to highlight most of the same relatively higher emitting machines.

4.3 Idle Accessory Load

One issue that was briefly examined during this larger effort was the level of accessory idle load to use for child rating tests. As part of the development of the off-road LLC, the idle accessory load was determined as 3.5% of maximum engine power. In the original Tier 5 demonstration, the calculation was implemented on the maximum power matching the rating that was being tested. So, for the 187 kW Nominal rating, an idle load of 78 Nm was used, while for the 126 kW Child rating, an idle load of 53 Nm was used. However, for this added work, CARB asked SwRI to examine the impact of using a Nominal idle load for all ratings. To simulate this, SwRI ran using the Nominal load of 78 Nm for all cycles regardless of rating. This change was also examined on the off-road LLC itself.

The impact of idle load settings on exhaust temperature is shown in Figure 37, while tailpipe NO_x emissions for both idle load settings are shown in Figure 38.

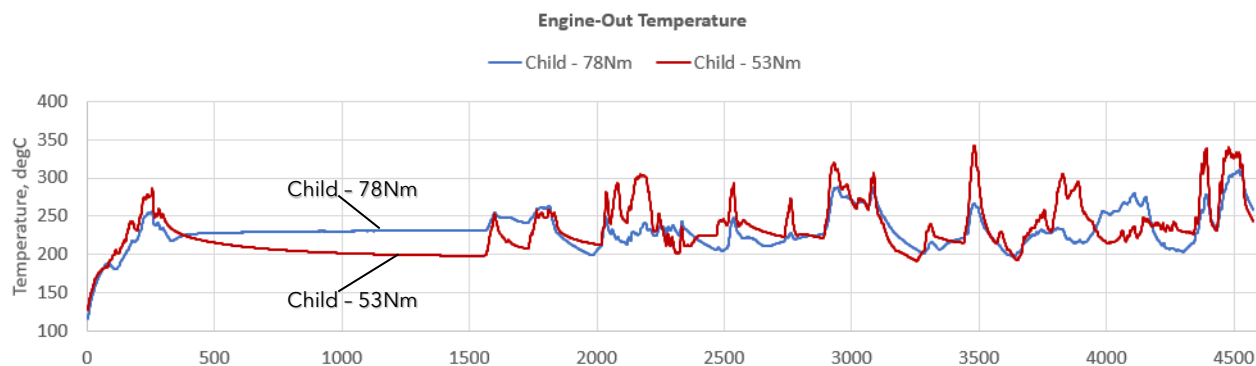


FIGURE 37. EXHAUST TEMPERATURE COMPARISON AT DIFFERENT IDLE LOADS FOR CHILD RATING ON LLC

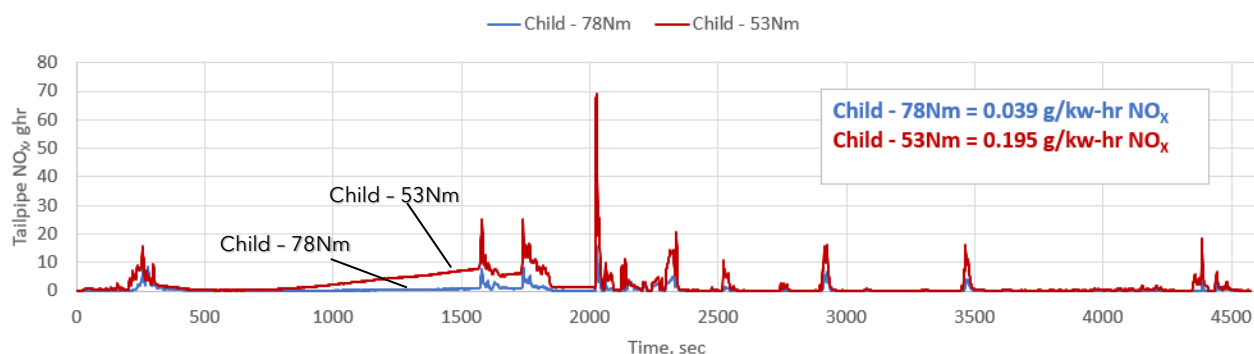


FIGURE 38. TAILPIPE NO_x COMPARISON AT DIFFERENT IDLE LOADS FOR CHILD RATING ON LLC

Engine data indicated that the change in accessory idle load resulted in the engine idling at about 1.5 bar brake mean effective pressure (BMEP) at 78 Nm, up from about 1 bar BMEP at 53 Nm. This was enough to increase the idle fuel rate by about 30%, and with no significant change in airflow, the air-fuel-ratio dropped substantially, resulting in a 30°C increase in exhaust temperature at idle, as can be seen in Figure 37 during the long idle segment in the LLC from 500 to 1500 seconds. This resulted in MFC temperatures that went from 190°C to 220°C, resulting in a large improvement in NO_x reduction capability. A more complete set of LLC data for testing at various idle loads is given in Table 9.

This change was also examined on two of the field cycles, Cycle 01 and Cycle 14, both of which were run using the Child rating. Table 10 shows bin-MAW emission results for both cycles with both the higher and lower idle thresholds. In these cases, it is interesting to note that the field cycles did not show the same behavior as the LLC, although neither of these cycles contains an extended idle event like the one in the LLC. However, that idle event also came from the field and represents roughly a 90th percentile of idle duration in field operations. Lacking the long idle, it was generally observed that the field cycles with the higher idle load actually had slightly higher bin

emission levels for Bins B and C, though the lower idle loads appeared to have more N₂O emissions.

TABLE 9. EMISSION RESULTS FOR LLC TESTING AT DIFFERENT IDLE LOADS

Run Number	Rating	Idle Load, Nm	DSF Active ?	Updated Calibration ?	NO_x, g/kW-hr	CO₂, g/kW-hr	N₂O, g/kW-hr
8148	Child	53	Yes	No	0.050*	895	0.096**
2851	Child	78	Yes	No	0.007	927	0.183
2933	Child	78	Yes	Yes	0.003	938	0.152
2466	Child	53	No	No	0.018	1041	-
2854	Child	78	No	No	0.006	1062	0.312
2889	Child	78	No	Yes	0.039	1057	0.181
* Not re-tested with most up to date controls architecture, value may be high ** Not re-tested with most up to date controls architecture, value may be low							

TABLE 10. XB-MAW RESULTS FOR FIELD CYCLES TESTED AT DIFFERENT IDLE LOADS

Cycle-Rating	Bin A		Bin B		Bin C		Bin B/C
	n***	NO_x, g/hr**** *	n	NO_x, g/kW- hr	n****	NO_x, g/kW- hr	NO_x, g/kW- hr
Thresholds at CF 1.5	min 2,400	15*	B+C min 10,000	0.090	B+C min 10,000	0.060	0.070**
Thresholds at CF 2.0		20*		0.120		0.080	0.097**
1 - 126 kW, 78 Nm	6754	0.0 (- 0.02)	12187	0.033	8447	0.022	0.027
1 - 126 kW, 53 Nm	6833	0.0 (- 0.11)	12205	0.024	8350	0.018	0.021
14 - 126 kW, 78 Nm	<u>2013</u>	0.4	15347	0.027	263	0.200	0.032
14 - 126 kW, 53 Nm	<u>2201</u>	0.1 (0.07)	15134	0.016	288	0.243	0.023
1 - 187 kW, 78 Nm	7579	0.0 (0.02)	13380	0.026	6429	0.012	0.020
* Calculated Idle Standard for this engine at 187 kW is 10 g/hr ** Bin B/C possible threshold based on 33% LLC and 67% NRTC weighting *** Underlined values are below 2,400 minimum requirement **** Bolded values are a very low number of windows for Bin C quantification ***** Values in parenthesis are as measured, note negative measured values set to zero as specified							

4.4 Recalibration for Better N₂O Control

Following the initial test results for the various field cycles, the data was examined to determine if there were any areas where performance was not meeting expectations in a way that would indicate a problem, or a weakness with the calibration. Field cycle tailpipe NO_x performance was generally reflective of the levels expected based on the regulatory cycle results. However, it was noted that on some of the lower load field cycles N₂O emissions were very high, in some cases more than 3X the proposed NRTC standard of 0.15 g/kW-hr. This was the case for Cycles 01, 12, and 14 run using the Child Rating. Although no limit values are proposed for field cycle N₂O, this behavior indicated that the calibration was targeting too much stored ammonia during sustained low load operations. Excess stored ammonia leads to ammonia slip through the system at various stages during temperature ramps, which can in turn result in N₂O formation over the DOC and/or slip catalysts.

It was decided to adjust the calibration to help reduce the buildup of excess ammonia storage under these conditions. This would address the N₂O issues, but it might also have a negative impact on tailpipe NO_x levels. The recalibration focused on modest reductions to low load storage targets at lower NO_x flux levels, as well as re-tuning of the storage profile control to more aggressively control the buildup of higher storage levels towards the back of the SCR catalysts. This did not impact the NRTC or RMC, but it did have an impact on LLC NO_x for the child rating, as seen in Table 9, although the tailpipe NO_x was still below the proposed standard of 0.060 g/kW-hr. The result of the recalibration is shown in Table 11, with N₂O levels reduced from nearly 0.5 g/kW-hr to 0.33 g/kW-hr (a 34% reduction), while Bin B and C NO_x levels increased by only 6 to 7 mg/kW-hr and were still well below the proposed thresholds. The LLC result indicated that there was not much room for further calibration without sacrificing too much margin on that cycle. The lower N₂O breakthroughs in several areas can be seen in Figure 39.

TABLE 11. XB-MAW RESULTS FOR FIELD CYCLE 01 BEFORE AND AFTER RECALIBRATION WITH CHILD RATING

Cycle-Rating	Bin A		Bin B		Bin C		Bin B/C	N ₂ O, g/kW-hr
	n	NO _x , g/hr***	n	NO _x , g/kW-hr	n	NO _x , g/kW-hr	NO _x , g/kW-hr	
Thresholds at CF 1.5	min 2,400	15*	B+C min 10,000	0.090	B+C min 10,000	0.060	0.070**	
Thresholds at CF 2.0		20*		0.120		0.080	0.097**	
1 - 126 kW	6754	0.0 (-0.02)	12187	0.033	8447	0.022	0.027	0.493
1 - 126 kW, new cal	6780	0.0 (-0.03)	12105	0.039	8501	0.029	0.033	0.329
* Calculated Idle Standard for this engine at 187 kW is 10 g/hr ** Bin B/C possible threshold based on 33% LLC and 67% NRTC weighting *** Values in parenthesis are as measured, note negative measured values set to zero as specified								

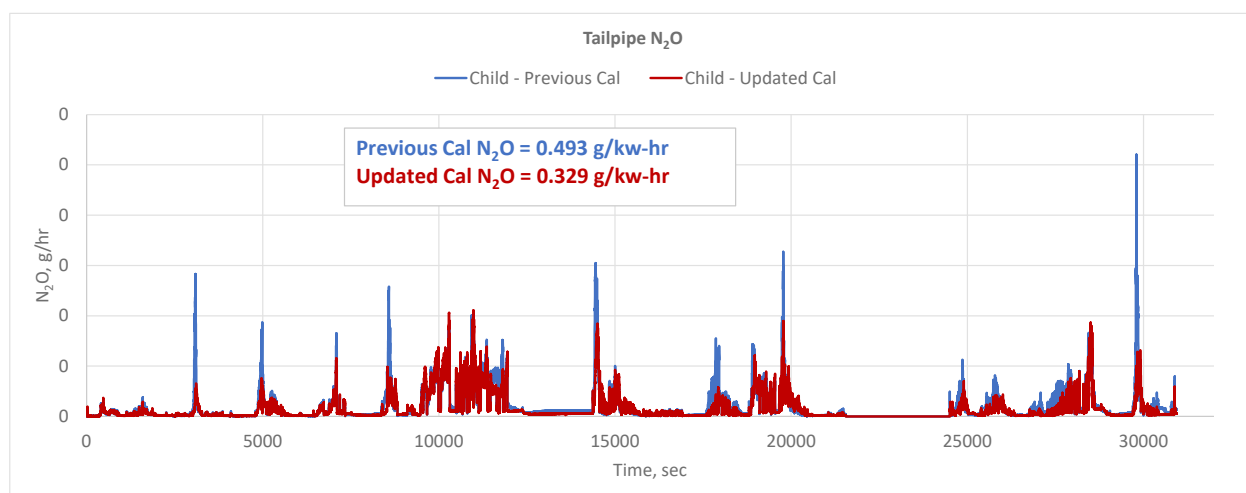


FIGURE 39. N₂O EMISSIONS FOR FIELD CYCLE 01 BEFORE AND AFTER RECALIBRATION WITH CHILD RATING

4.5 Alternate Package Configuration

As noted earlier, one of the evaluations that was conducted was to examine the performance of the Tier 5 system using the Alternate Package configuration that was originally developed by EMA for a supplemental study on packaging impacts and low ambient temperature effects on the performance of the Tier 5 system. The Alternate Package configuration was described earlier. This configuration was evaluated using Cycle 01 and it was run on the Child rating, because that was considered the rating that would potentially place more stress on the two-can AT configuration.

A summary of results for Field Cycle 01 in both the Base Tier 5 and Alternate Configuration is given in Table 12. The data shows that for this field cycle, the Alternate Package configuration actually performed better than the Base Tier 5 package. NO_x emissions with the Alternate Package were significantly better on Bin B and Bin C, and N₂O levels were half those observed on the Base Package and actually met the 0.15 g/kw-hr NRTC standard. SCR catalyst temperatures for both configurations are shown in Figure 40, and NO_x levels are compared in Figure 41.

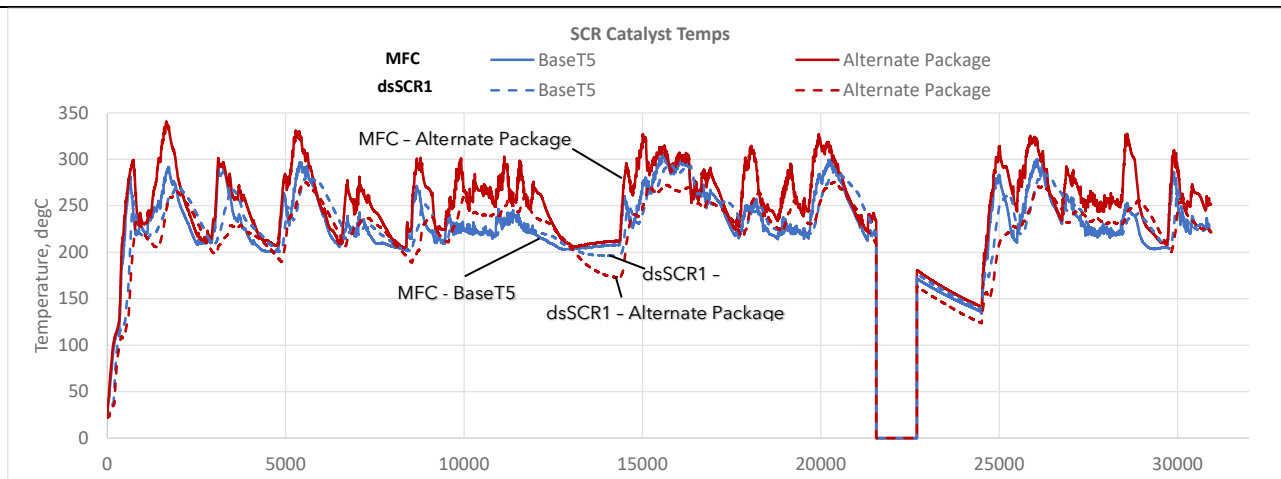
TABLE 12. XB-MAW RESULTS FOR DIFFERENT PACKAGE CONFIGURATIONS USING FIELD CYCLE 01

Cycle-Rating	Bin A		Bin B		Bin C		Bin B/C	N ₂ O, g/kW-hr
	n	NO _x , g/hr***	n	NO _x , g/kW-hr	n	NO _x , g/kW-hr	NO _x , g/kW-hr	
Thresholds at CF 1.5	min 2,400	15*	B+C min 10,000	0.090	B+C min 10,000	0.060	0.070*	
Thresholds at CF 2.0		20*		0.120		0.080	0.097*	
1 - 126 kW, new cal	6780	0.0 (-0.03)	12105	0.039	8501	0.029	0.033	0.329
1 - 126 kW Alternate Pkg, new cal	6689	0.0 (-0.05)	11396	0.028	9304	0.016	0.021	0.144

* Calculated Idle Standard for this engine at 187 kW is 10 g/hr

** Bin B/C possible threshold based on 33% LLC and 67% NRTC weighting

*** Values in parenthesis are as measured, note negative measured values set to zero as specified

**FIGURE 40. SCR CATALYST TEMPERATURES FOR FIELD CYCLE 01 IN BASE TIER 5 AND ALTERNATE PACKAGE CONFIGURATIONS**

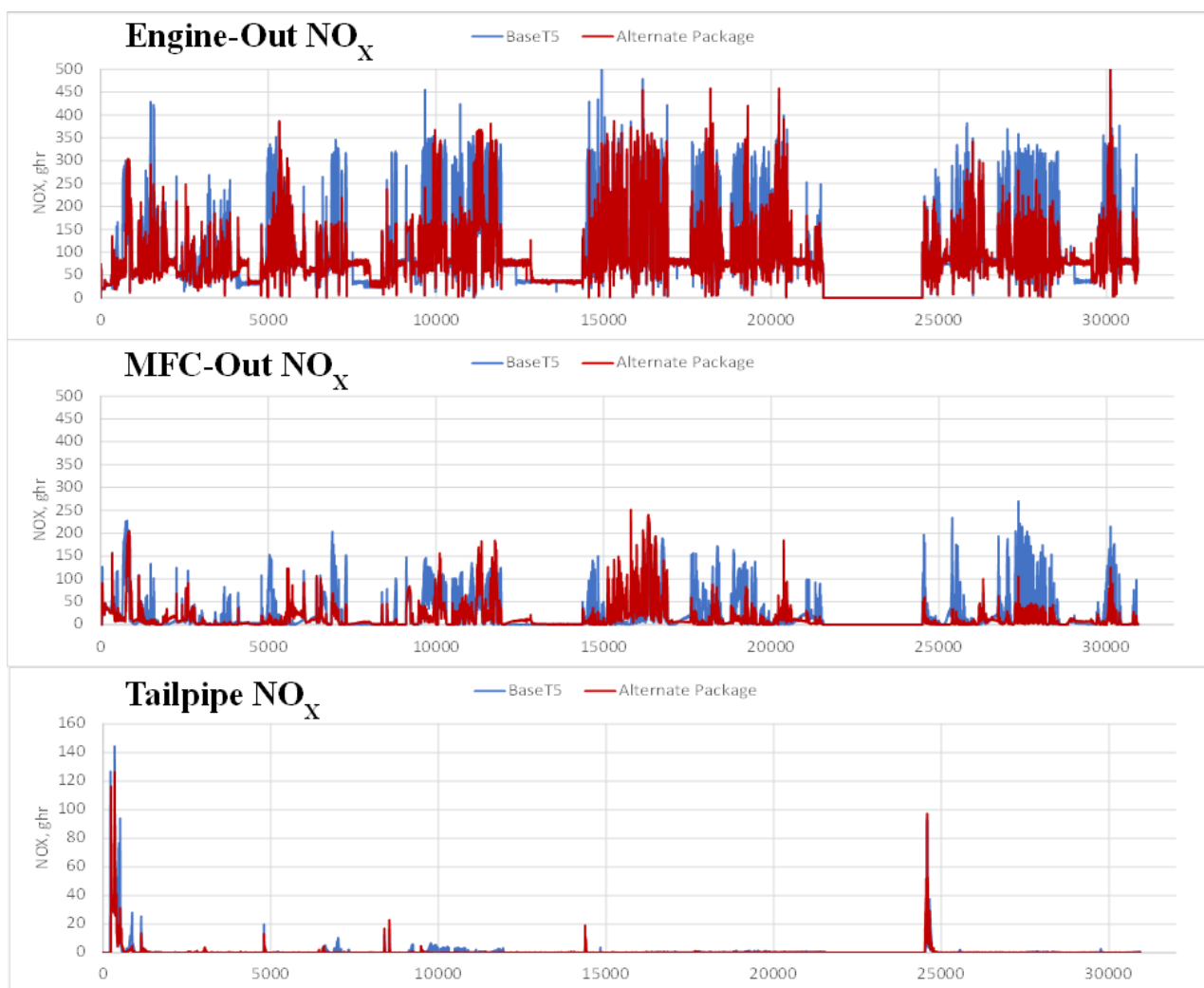


FIGURE 41. NO_x EMISSIONS FOR FIELD CYCLE 01 IN BASE TIER 5 AND ALTERNATE PACKAGE CONFIGURATIONS

Although downstream SCR temperatures are lower with the Alternate Package, the upstream MFC temperatures are actually higher. This meant that the MFC was able to perform better and take up more of the load of NO_x reduction on this lower load field cycle. In addition, the lower downstream temperatures meant that the engine stayed in thermal management longer, resulting in lower engine-out NO_x levels in those portions of the field cycle, as can be seen in Figure 41. This resulted in better MFC performance, and less of a burden on the downstream system for additional NO_x reduction. In addition, the higher MFC temperatures meant that MFC ammonia storage levels were lower and the generation of N₂O across the MFC was also lower, leading ultimately to lower tailpipe N₂O. This can be seen in the N₂O emission behavior given in Figure 42.

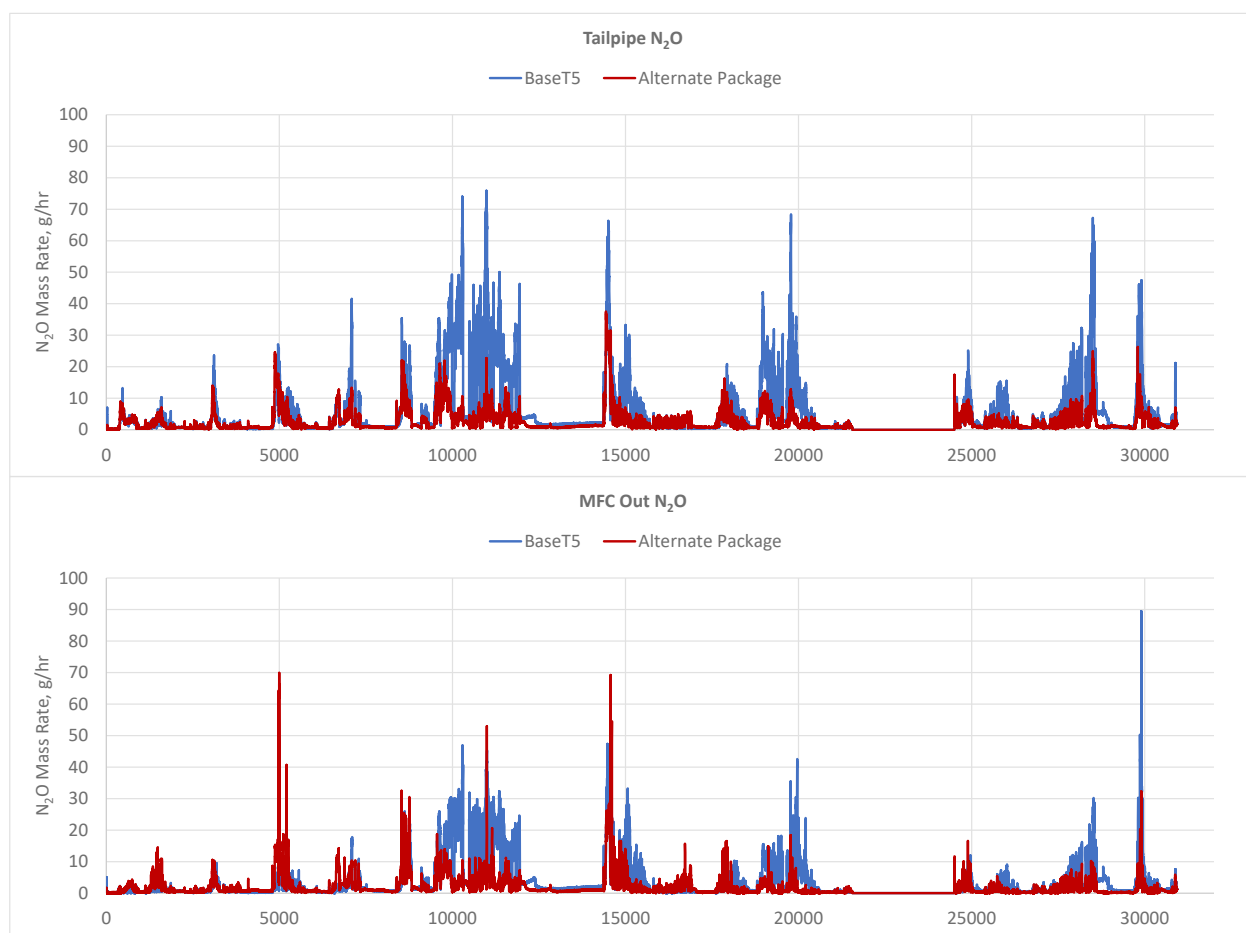


FIGURE 42. N₂O EMISSIONS FOR FIELD CYCLE 01 IN BASE TIER 5 AND ALTERNATE PACKAGE CONFIGURATIONS

In the end it was clear that in this case, the Alternate Package performed measurably better than the Base Tier 5 package, and in any case, bin-MAW NO_x emissions were well below the thresholds for both packages. This indicated that the revised calibration and controls scheme remained effective across packaging changes.

4.6 Impact of DSF

Most of the field cycle testing was run with DSF enabled, and that technology serves as one of the thermal management levers in the system, alongside the rest of the thermal management strategy. However, a few tests were also conducted without DSF to understand how much that technology was contributing to the overall NO_x performance that was being observed on the field cycles. It was considered that this DSF impact testing should focus on the cycles where it was expected that DSF would have the largest impact. This was anticipated to be during lower load duty cycles, therefore testing without DSF was conducted on Cycle 01 and Cycle 14, both with the

Child Rating. Table 13 shows bin-MAW results with and without DSF active for both cycles. The data do not show a clear trend with respect to the impact of DSF on tailpipe NO_x emissions. In the case of Cycle 01 the NO_x data was slightly better without DSF active, though N₂O was higher. On the other hand, for the even lower load Cycle 14, NO_x was significantly lower with DSF, while N₂O was about the same with and without DSF. For both of these low load field cycles, using DSF resulted in a significant CO₂ improvement, as expected.

TABLE 13. XB-MAW RESULTS FOR FIELD CYCLES WITH AND WITHOUT DSF

Cycle-Rating	Bin A		Bin B		Bin C		Bin B/C	CO ₂ , g/kW-hr	N ₂ O, g/kW-hr
	n***	NO _x , g/hr *****	n	NO _x , g/kW-hr	n****	NO _x , g/kW-hr	NO _x , g/kW-hr		
Thresholds at CF 1.5	min 2,400	15*	B+C min 10,000	0.090	B+C min 10,000	0.060	0.070*		
Thresholds at CF 2.0		20*		0.120		0.080	0.097*		
1 - 126 kW, with DSF	6780	0.0 (-0.03)	12105	0.039	8501	0.029	0.033	966	0.329
1 - 126 kW no DSF	<u>1595</u>	0.1 (0.06)	16547	0.035	9246	0.021	0.029	1018	0.433
14 - 126 kW with DSF	<u>2013</u>	0.4	15347	0.027	263	n/a	0.032	849	0.218
14 - 126 kW no DSF	<u>992</u>	0.3	16124	0.051	507	n/a	0.059	918	0.250
* Calculated Idle Standard for this engine at 187 kW is 10 g/hr ** Bin B/C possible threshold based on 33% LLC and 67% NRTC weighting *** Underlined values are below 2,400 minimum requirement **** Bolded values are a very low number of windows for Bin C quantification ***** Values in parenthesis are as measured, note negative measured values set to zero as specified									

A comparison of SCR temperatures with and without DSF on Cycle 14 is given in Figure 43, while thermal management behavior is shown in Figure 44. The data indicate higher temperatures with DSF active for both upstream and downstream catalysts. For this particular duty cycle, DSF generally raised temperatures above the 220°C mark, resulting in better SCR performance.

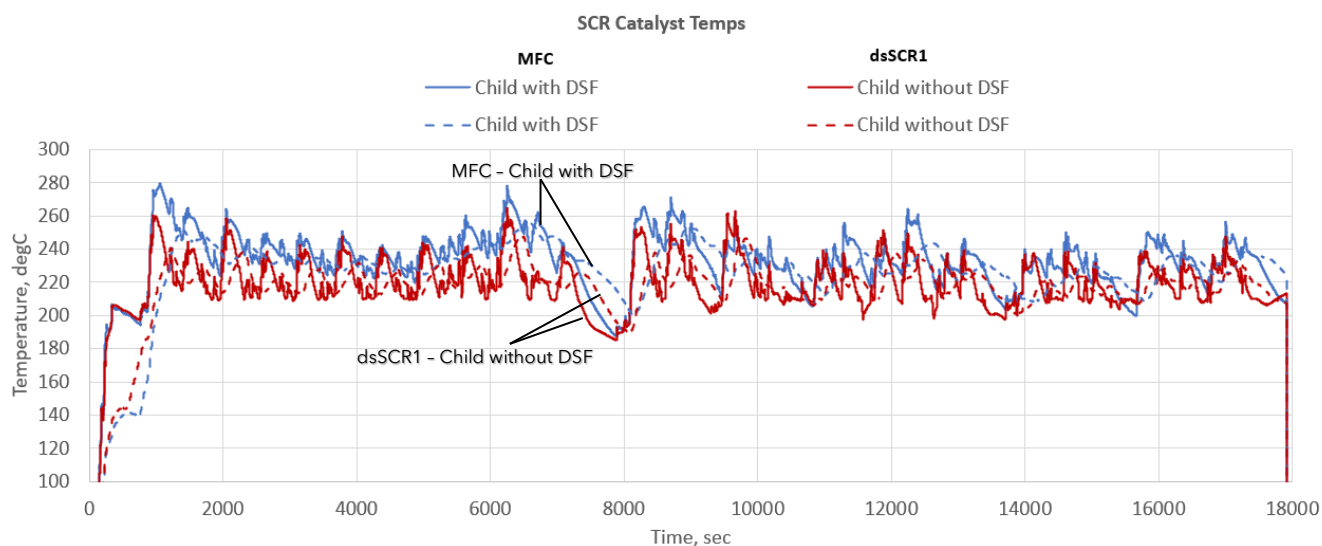


FIGURE 43. IMPACT OF DSF ON FIELD CYCLE 14 SCR TEMPERATURES

The impact of this change can be seen in the significantly reduced use of thermal management observed in Figure 44. With DSF, much of the cycle is spent with no thermal management modes active, with the DSF itself serving to maintain cycle temperatures. On the other hand, without DSF, much of the cycle is spent in thermal management, however the temperatures are still lower. The resulting NO_x behavior is shown in Figure 45 with MFC-out NO_x levels being much lower with DSF due to the higher temperatures, resulting eventually in fewer tailpipe NO_x breakthroughs.

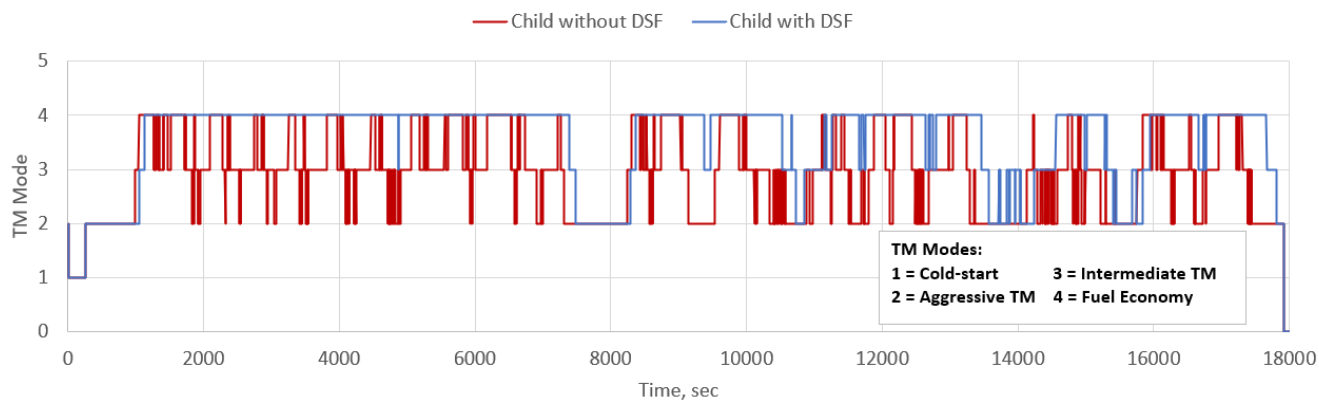


FIGURE 44. IMPACT OF DSF ON THERMAL MANAGEMENT BEHAVIOR OVER FIELD CYCLE 14 WITH CHILD RATING

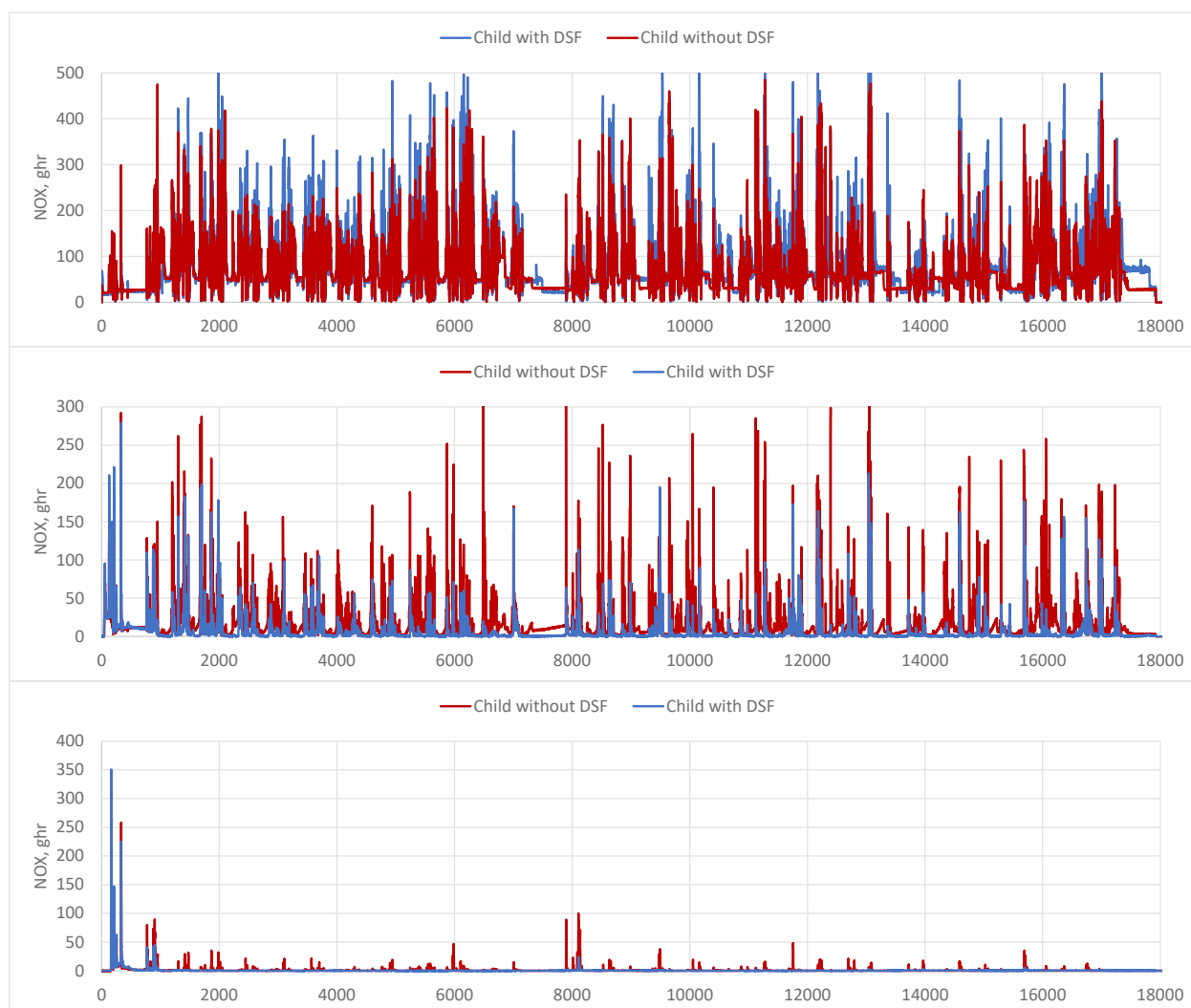


FIGURE 45. IMPACT OF DSF ON NO_x EMISSIONS OVER FIELD CYCLE 14 WITH CHILD RATING

However, with the somewhat higher loads on Cycle 01 (30% of windows in Bin C with Cycle 01 as compared to less than 1% in Bin C for Cycle 14), similar benefits are not observed, and the tailpipe NO_x level is actually marginally better without DSF active. This indicates that the impact of DSF is highly cycle dependent. It should be noted that even on Cycle 14 without DSF, tailpipe NO_x levels are still below the proposed thresholds, but not by as large a margin as with DSF active.

4.7 Comparison of CO₂-Based and Torque-Based Calculations

For all of the previous bin-MAW results in this report, the values given were generated using CO₂-based calculations, as discussed earlier in Section 2.7. This was done primarily because all the CAN variables needed to calculate net broadcast torque in engineering units were not available for this engine. Therefore, CO₂-based calculations were used to generate a result that would be the closest to an actual in-use measurement, given that any PEMS error related to CO₂ would likely be small.

However, another part of this program's scope was to examine the potential different behaviors between torque-based and CO₂-based calculations. Given that a broadcast torque was not available, torque-based calculations were performed using the Lab measured torque. It should be noted that this value is likely more accurate than the ECM-predicted broadcast value, especially under light load conditions. Nevertheless, it is still possible to look at different behaviors between the two calculation methods.

There are two primary ways the calculation method can cause the results to vary. The first is that the choice of calculation method can affect the bin sorting of individual windows. This is because the normalized CO₂ and normalized power do not scale in the same way as each other. That discrepancy can result in windows being assigned into different bins, especially when the normalized value is near one of the bin thresholds of 8% and 25%. The second way that the value can be shifted concerns how the method impacts the denominator of the brake-specific calculation used for Bins B and C.

An example of the bin sorting impacts can be seen in Figure 46 which shows the bin allocation of NO_x across all 3 bins, along with the normalized CO₂ and power values and the bin thresholds. This result is for a test run for Cycle 01 using the Child Rating with the Revised calibration. The resulting values for both 2B-MAW and 3B-MAW by both methods, along with the number of windows in each bin, are given in Table 14. A good example of results landing in different bins can be seen between the Bin B and Bin C graphs in the range near 10,000 seconds where it can be seen that the normalized CO₂ (yellow) is above the 25% threshold while the normalized torque (power, purple) is below that same threshold. This causes the associated NO_x windows to be placed in Bin C for CO₂-based calculations, and in Bin B for torque-based calculations.

Figure 47 shows a zoomed in comparison example between normalized CO₂ and normalized torque based calculations. Clear differences are visible, with some values during accelerations being twice as high for CO₂ as they are for power. Note that in the range 9600 and 10400 seconds, many windows are sorted into Bin C using the CO₂-based calculation, while almost none are sorted into Bin C using the torque-based calculation, leading to very different results for both Bin B and Bin C. It should be noted that these differences could be even larger for broadcast torque, because there are often larger errors associated with that value compared to the Lab measured torque used here. Previous efforts [5][12] have indicated the broadcast torque errors, especially at light load, can be as high as 30%, and that the final impact of these errors will depend heavily on the duty cycle of a given test.

The results in Table 14 shows the impact of these changes. There are far fewer windows in Bin C for torque-based calculations, with nearly all return-to-service events having been shifted into Bin B. As a result, the Bin C result for torque-based calculations is only 3 mg/kW-hr, while the CO₂-based value is 29 mg/kW-hr. The number of windows in each bin show very large discrepancies. The Overall Cycle NO_x

result differences give an indication of the differences caused by the change in the brake-specific denominator. It should be noted that these discrepancies will vary for each different duty cycle and data set, such that a clear trend will be difficult to establish.

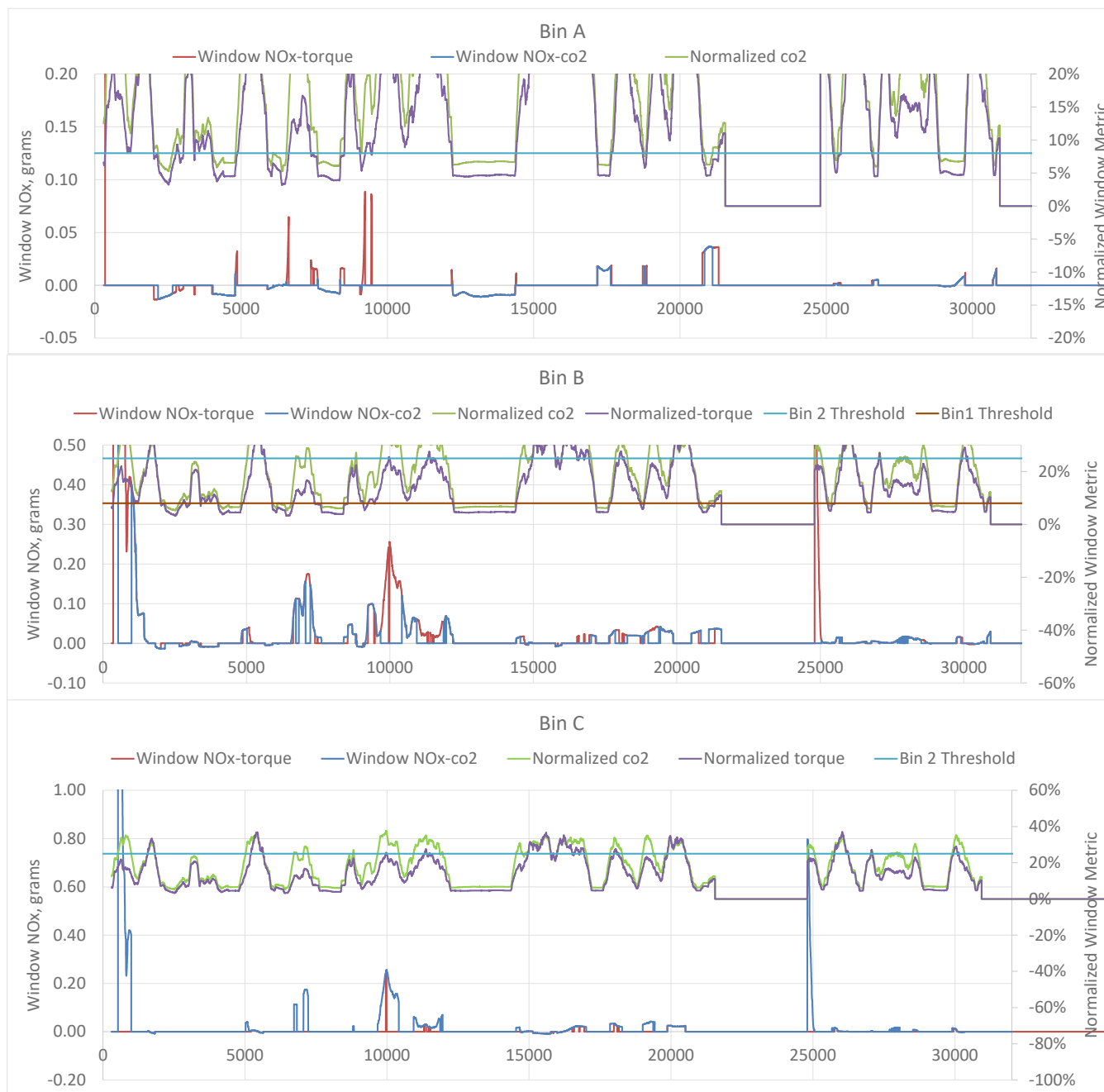


FIGURE 46. WINDOW ALLOCATION ACROSS 3 BINS FOR FIELD CYCLE 01 - CHILD RATING, UPDATED CALIBRATION

It should be noted that a 2B-MAW method will be less susceptible to these problems because there are fewer sorting decisions to be made, thus reducing the number of possibilities for different bin sorting of a given window.

TABLE 14. XB-MAW RESULTS FOR CO₂-BASED AND TORQUE-BASED METHODS

-	Bin A		Bin B		Bin C		Overall	-
-	NO _x	n	NO _x	n	NO _x	n	NO _x	n
-	g/hr	-	g/kW-hr	-	g/kW-hr	-	g/kW-hr	-
3B-MAW								
CO ₂	-0.03	6780	0.039	12105	0.029	8501	0.030	27386
Torque	0.12	8829	0.060	14602	0.003	3955	0.038	27386
2B-MAW								
CO ₂	-0.03	6780	0.033	20606	-	-	0.030	27386
Torque	0.12	8829	0.041	18557	-	-	0.038	27386

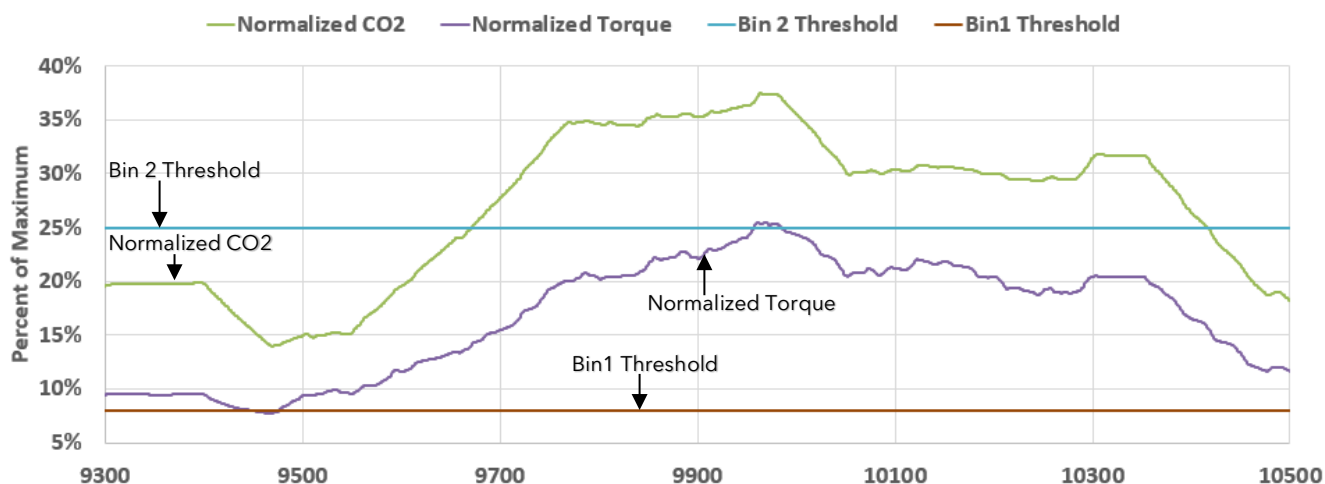


FIGURE 47. COMPARISON OF NORMALIZED CO₂ AND NORMALIZED POWER DURING A SPECIFIC LOAD EVENT

A comparison of xB-MAW results for all of the field cycles between CO₂-based and torque-based calculations is given in Table 15. Torque-based calculation results are given in the lighter shaded rows, which are also labeled in the Method column as "Torque." As noted earlier there is no clear trend as to the magnitude or direction of the discrepancies between CO₂-based bin values and torque-based bin values. Sometimes the values are quite close, and other times they vary by an order of magnitude. These different behaviors changed based on the individual duty cycles.

Table 15 also shows calculated BSNO_x over the full cycle for both methods, even though this is not normally an output of the calculations. However, this can give more

insight into the impact of the work denominator for both calculation methods on the emission results, independent of bin sorting impacts. The impact of calculation method on the work denominator can vary based on where the overall average load falls. This is due to the fact that the relationship between power and BSCO₂ (which is used to scale CO₂-based bin NO_x values) changes with load, with those values rising as load gets lower. When the overall values are relatively near those of the NRTC, then the two calculations can be relatively close. At lighter loads and higher loads, the discrepancies will increase the further BSCO₂ moves from the NRTC value, although there are much more pronounced errors at light loads, with the torque-based method resulting in somewhat higher values. It is important to consider these impacts when final bin standards are set for in-use testing.

TABLE 15. FIELD CYCLE XB-MAW RESULTS WITH BOTH CO₂-BASED AND TORQUE-BASED CALCULATIONS

Field Cycle	Rating	Method	Tailpipe NO _x						-	-
			2-Bin MAW		3-Bin MAW			Whole Cycle g/kW-hr	N ₂ O, g/kW-hr	CO ₂ , g/kW-hr
			Bin A	Bin B	Bin A	Bin B	Bin C			
			g/hr	g/kW-hr	g/hr	g/kW-hr	g/kW-hr			
01-Nominal	187	CO ₂	0.02	0.020	0.02	0.027	0.012	0.018	0.328	862
		Torque	0.21	0.023	0.21	0.030	0.002	0.023	-	-
01-Child	126	CO ₂	-0.03	0.033	-0.03	0.039	0.029	0.030	0.329	966
		Torque	0.12	0.041	0.12	0.060	0.003	0.038	-	-
04-Nominal	187	CO ₂	-0.03	0.019	-0.03	0.038	0.018	0.020	0.045	691
		Torque	1.08	0.017	1.08	0.017	0.017	0.020	-	-
07-Nominal	187	CO ₂	0.69	0.025	0.69	0.053	0.024	0.034	0.071	673
		Torque	0.77	0.024	0.77	0.069	0.023	0.033	-	-
09-Child	126	CO ₂	0.13	0.015	0.13	0.010	0.016	0.015	0.051	720
		Torque	0.11	0.015	0.11	0.021	0.013	0.015	-	-
11-Nominal	187	CO ₂	0.01	0.017	0.01	0.011	0.017	0.016	0.067	701
		Torque	0.01	0.015	0.01	0.011	0.015	0.015	-	-
12-Child	126	CO ₂	-0.07	0.039	-0.07	0.046	0.011	0.039	0.225	847
		Torque	0.75	0.041	0.75	0.051	0.008	0.043	-	-
14-Child	126	CO ₂	0.35	0.032	0.35	0.027	0.198	0.032	0.218	849
		Torque	0.67	0.031	0.67	0.032	0.001	0.037	-	-

It is suggested, due to the inherent errors associated with broadcast torque, especially at light loads, that CO₂-based calculations might allow for more consistency

across different engines. In addition, for sensor-based calculations, CO₂ can be projected based on broadcast fuel flow, and this will tend to have less error than torque at lower loads [5].

Broadcast torque is generally calculated based on the J1939 parameters read from the CAN bus. This net output torque of the engine is calculated as the difference between the Actual Engine Percent Torque (J1939 SPN 513) and the Nominal Friction Percent Torque (J1939 SPN 514). Both are scaled to engineering units using the Engine Reference Torque (J1939 SPN 544) [11]. As engine torque gets lower, the difference between the values becomes small compared to the actual values, leading to increased sensitivity to measurement errors. It should be noted that there is no stated accuracy requirement for any of these parameters in J1939, and in particular, the Nominal Friction torque (which actually collects several loss terms together) is often estimated via an empirically calibrated table based on certain engine sensor measurements (which can vary by manufacturer). The accuracy of this parameter is directly related to the amount of calibration effort expended, and it is not clear how much of this effort can be expected for every given engine platform. Previous assessment of broadcast torque accuracy has indicated errors under lower load conditions as high as 30% [5][12]. Furthermore, unlike the case for on-highway engines (which often rely on these values for communication with transmissions) the availability and accuracy of these parameters for off-road engines varies.

5.0 SUMMARY AND CONCLUSIONS

A number of different areas related to in-use testing and the robustness of the Tier 5 demonstration engine-AT system were investigated as part of the expanded scope under this amendment. The emission control performance of the system was examined over a wide variety of duty cycles developed directly from real-world machine data, as described in detail in Section 3. Based on the results, a number of overall conclusions can be drawn about the performance of the Tier 5 system under field conditions.

A summary of tailpipe NO_x and N₂O test results for the Tier 5 demonstration engine over all of the field cycles is given in Table 16. The evaluation conditions included a wide range of conditions, including both Nominal and Child engine ratings, and results are shown both with DSF and (for selected cycles) without DSF. For the lighter load cycles (run with the low power Child rating), the results shown are generally after the calibration was optimized to help control N₂O levels better under sustained low load conditions. Results for both 2B-MAW and 3B-MAW are given, and the results given are for the CO₂-based in-use calculations because we did not have valid broadcast torque signals on this particular engine. Also, this choice avoided the low-load torque errors associated with broadcast torque. The impact of the methods is discussed in detail in Section 4.7.

The results generally indicate a significant working margin to the potential in-use thresholds for various scenarios. Many of the emission levels shown are at least 40% to 50% below the relevant thresholds, although there are a few cases where these margins are smaller, such as for Cycle 14 Bin B/C in a 2B-MAW scenario. It should be noted that all of these tests are run at normal ambient temperatures.

The results also show some difficulties for several duty cycles in meeting the required thresholds for a minimum number of windows in a given bin. In a 3B-MAW scenario, it appears that the combined requirement of 10,000 windows for Bins B and C may not be adequate for some equipment operations where there are less than 2400 Bin C windows. Further investigation is needed to assess how large the impact would be over a wider range of in-use operations. This suggests that separate minimums might be necessary for Bin B and C. The low number of Bin A windows can be addressed in the field by adding idle time to the end of a test shift-day, so this is not as much of an issue. In this case, moving to a 2B-MAW method from the proposed 3B-MAW method would mitigate these issues.

TABLE 16. FINAL XB-MAW RESULTS FOR FIELD CYCLES

Test Run No	Cycle-Rating	Bin A		Bin B		Bin C		Bin B/C	N ₂ O, g/kW-hr
		n***	NO _x , g/hr *****	n	NO _x , g/kW-hr	n****	NO _x , g/kW-hr	NO _x , g/kW-hr	
	Thresholds at CF 1.5	min 2,400	15*	B+C min 10,000	0.090	B+C min 10,000	0.060	0.070**	
	Thresholds at CF 2.0		20*		0.120		0.080	0.097**	
287 1	1 - 187 kW	7579	0.0 (0.02)	13380	0.027	6429	0.012	0.020	0.328
291 8	1 - 126 kW	6754	0.0 (-0.02)	12187	0.039	8447	0.029	0.033	0.329
290 4	1 - 126 kW no DSF	1595	0.06	16547	0.035	9246	0.021	0.027	0.430
284 5	4 - 187 kW	3661	0.0 (-0.03)	5763	0.038	24698	0.018	0.019	0.045
288 5	7 - 187 kW	6501	0.7	4166	0.053	30846	0.024	0.025	0.071
287 4	9 - 126 kW	2910	0.1	13477	0.010	12506	0.016	0.015	0.051
284 8	11 - 187 kW	3111	0.01 (0.006)	3624	0.011	22328	0.017	0.017	0.067
286 1	12 - 126 kW	214	0.0 (-0.07)	14323	0.046	1544	0.011	0.039	0.225
285 7	14 - 126 kW	2013	0.4	15347	0.027	263	0.200	0.032	0.218
292 2	14 - 126 kW no DSF	992	0.3	16124	0.051	507	0.226	0.059	0.250

* Calculated Idle Standard for this engine at 187 kW is 10 g/hr

** Bin B/C possible threshold based on 33% LLC and 67% NRTC weighting

*** Underlined values are below 2,400 minimum requirement

**** Bolded values are a very low number of windows for Bin C quantification

***** Values in parenthesis are as measured, note negative measured values set to zero as specified

A visual summary of 2B-MAW results for these cycles is given in Figure 48. The results show the 8000-hour aged Tier 5 system generally at or below half the placeholder Bin B threshold, with the exception of Cycle 14 without DSF, which has a margin of 11 mg/kw-hr at a CF of 1.5. Bin A results are below the potential threshold by a factor of 20. A similar summary for 3B-MAW results is given in Figure 49. When comparing the results in these two charts, it is worth noting that any of the field cycles that showed a higher value for either Bin B or Bin C in the 3-bin scenario also showed one of the higher Bin B/C values in a 2-bin scenario. This indicates that the 2-bin method appears to highlight cases with higher emissions just as well as the 3-bin method. As a result, there should be no significant loss in compliance assurance with either the 2B-MAW or 3B-MAW method.

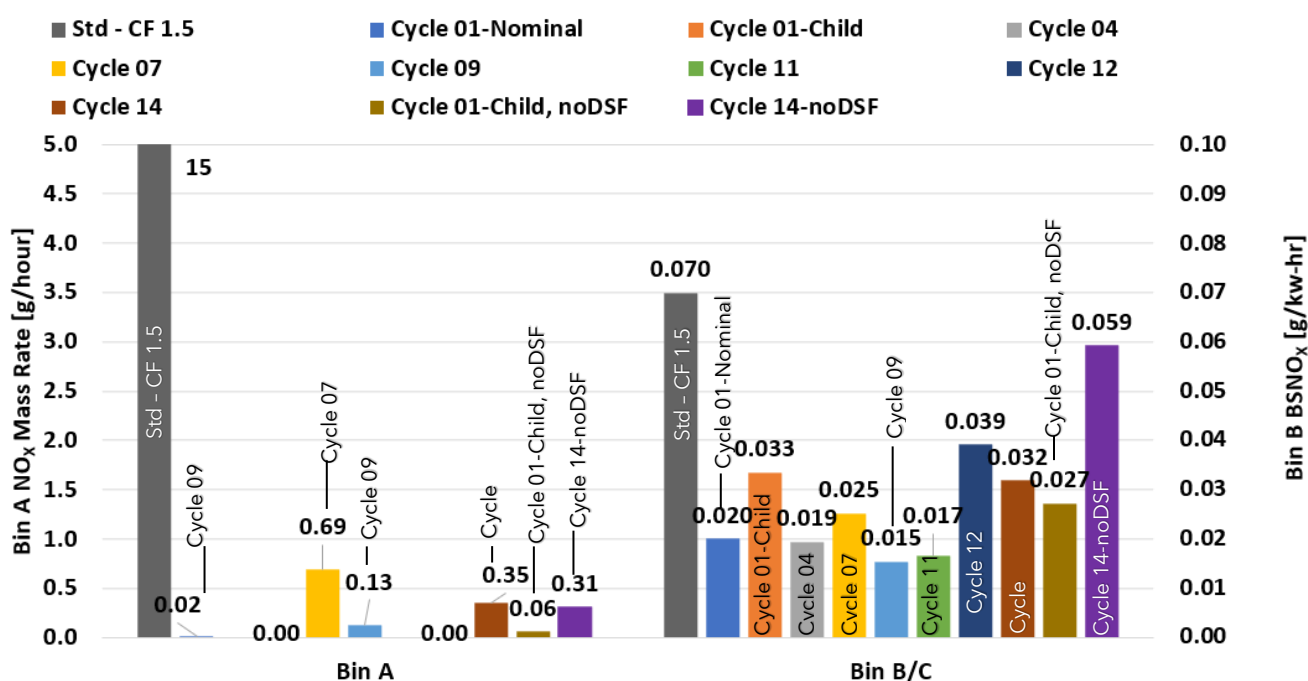


FIGURE 48. 2B-MAW NO_x RESULTS FOR FIELD CYCLES

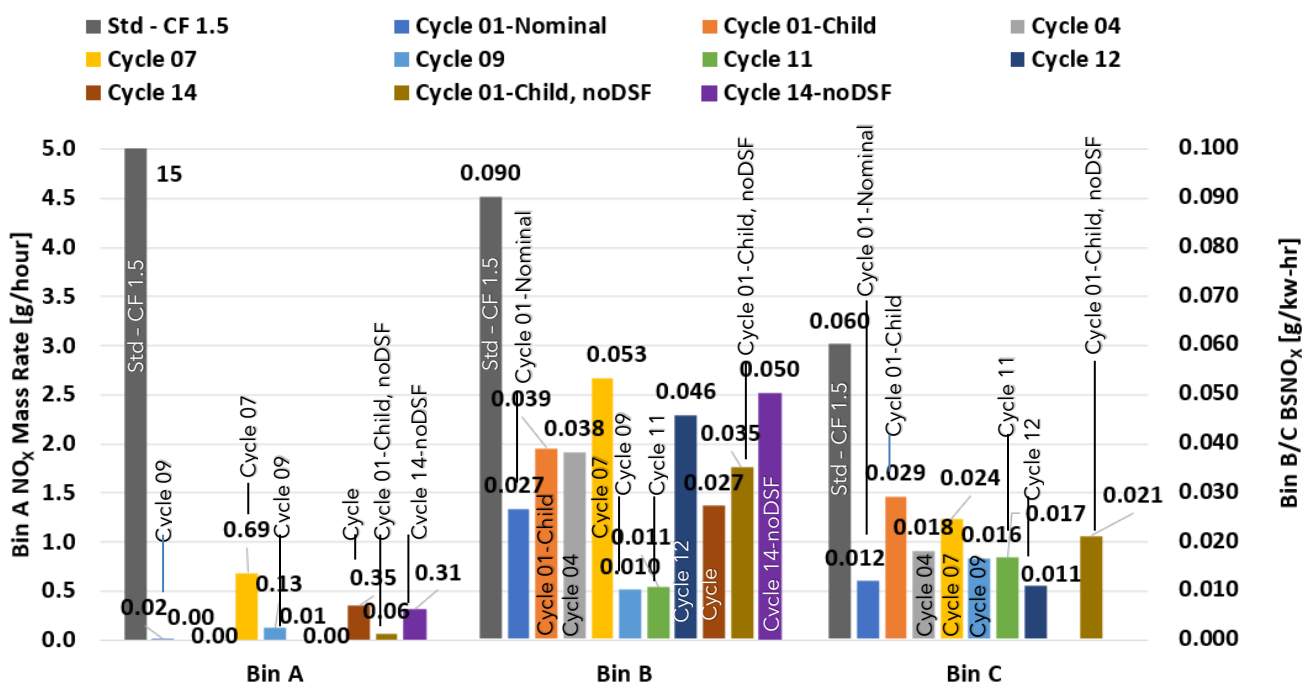


FIGURE 49. 3B-MAW NO_x RESULTS FOR FIELD CYCLES

Both CO₂-based and Torque-based calculations were examined for this effort. There was no clear trend in emission results in either 2B-MAW or 3B-MAW scenarios between the two calculations methods. Given that the CO₂ measurement is likely to suffer from smaller measurement errors than ECM broadcast torque, it is worth considering adopting CO₂-based calculations, similar to what has already been adopted for on-highway bin-MAW testing.

Moving to the use of Nominal rating idle load for lower power Child ratings does have some impact on the difficulty of the LLC, making it somewhat less difficult to reach Child rating compliance, with NO_x moving from 0.02 to below 0.01 g/kW-hr. However, this impact is less apparent for in-use testing, and if the use of nominal rating idle load remains representative of real-world operations, it should not pose a significant problem for emissions control.

6.0 REFERENCES

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12. SAE Digital Annex, J1939DA_202506.
13. "Determination of PEMS Measurement Allowances for Gaseous Emissions Regulated Under the Heavy-Duty Diesel Engine In-Use Testing Program," EPA420-R-08-005, February, 2008.

APPENDIX A - INDIVIDUAL NORMALIZED FIELD CYCLES

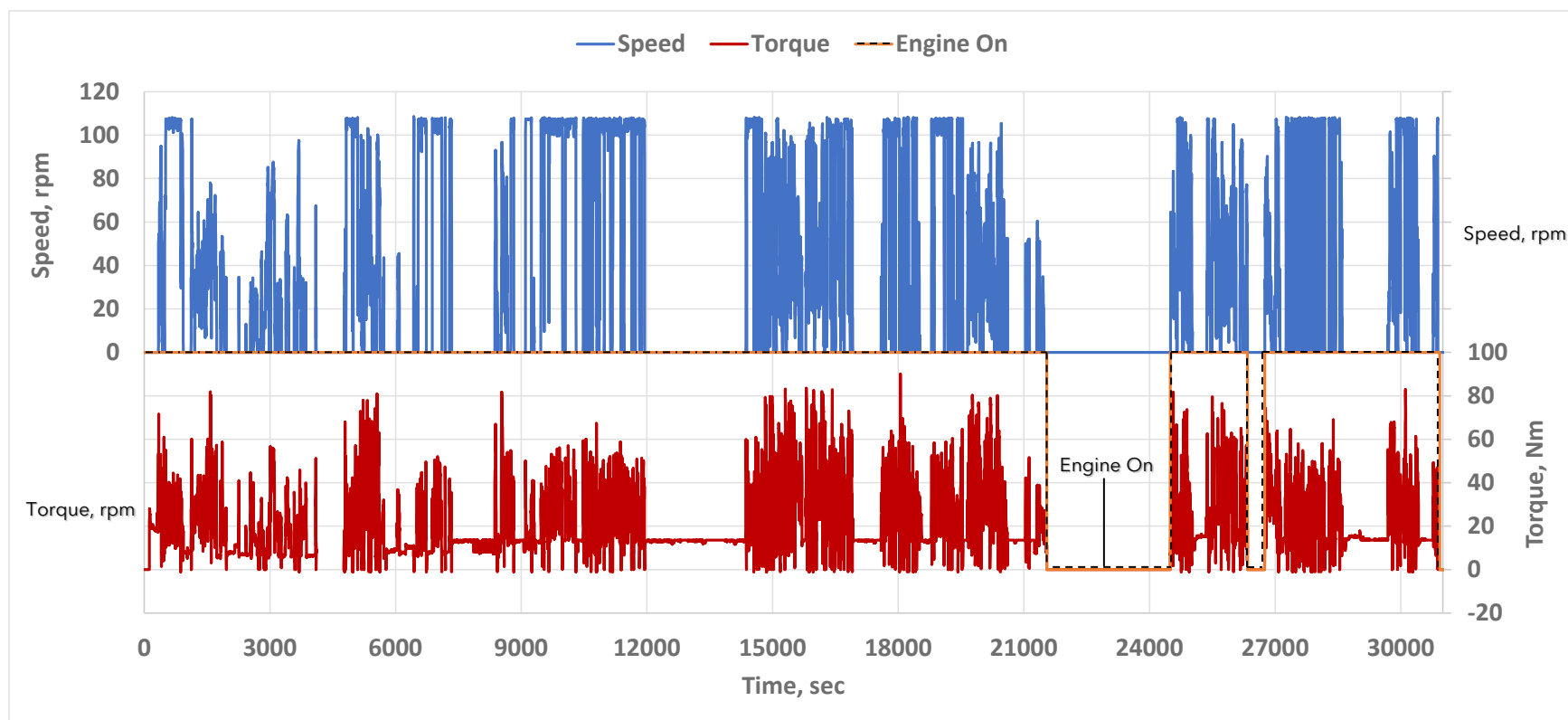


FIGURE 50. FIELD CYCLE 01 - BACKHOE, JOHN DEERE 4.5L

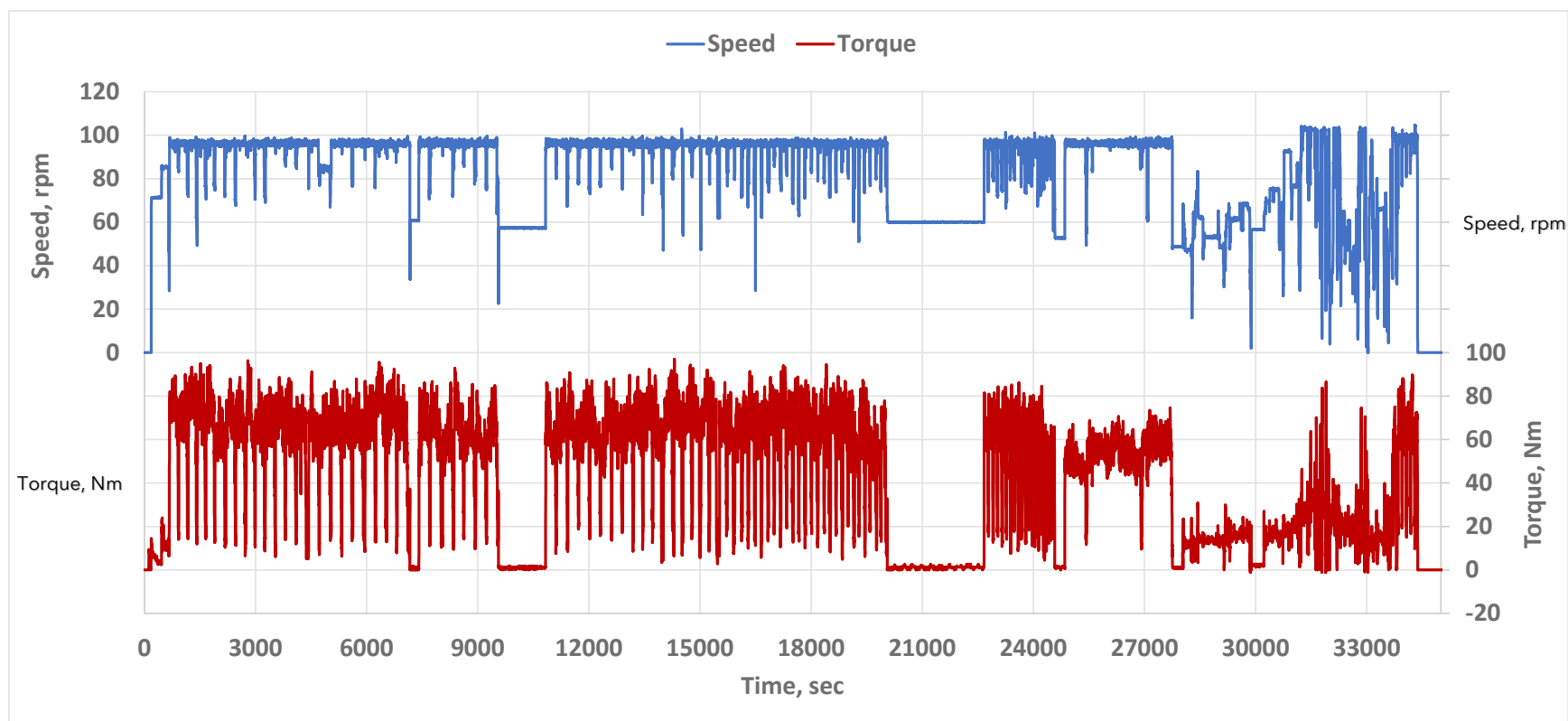
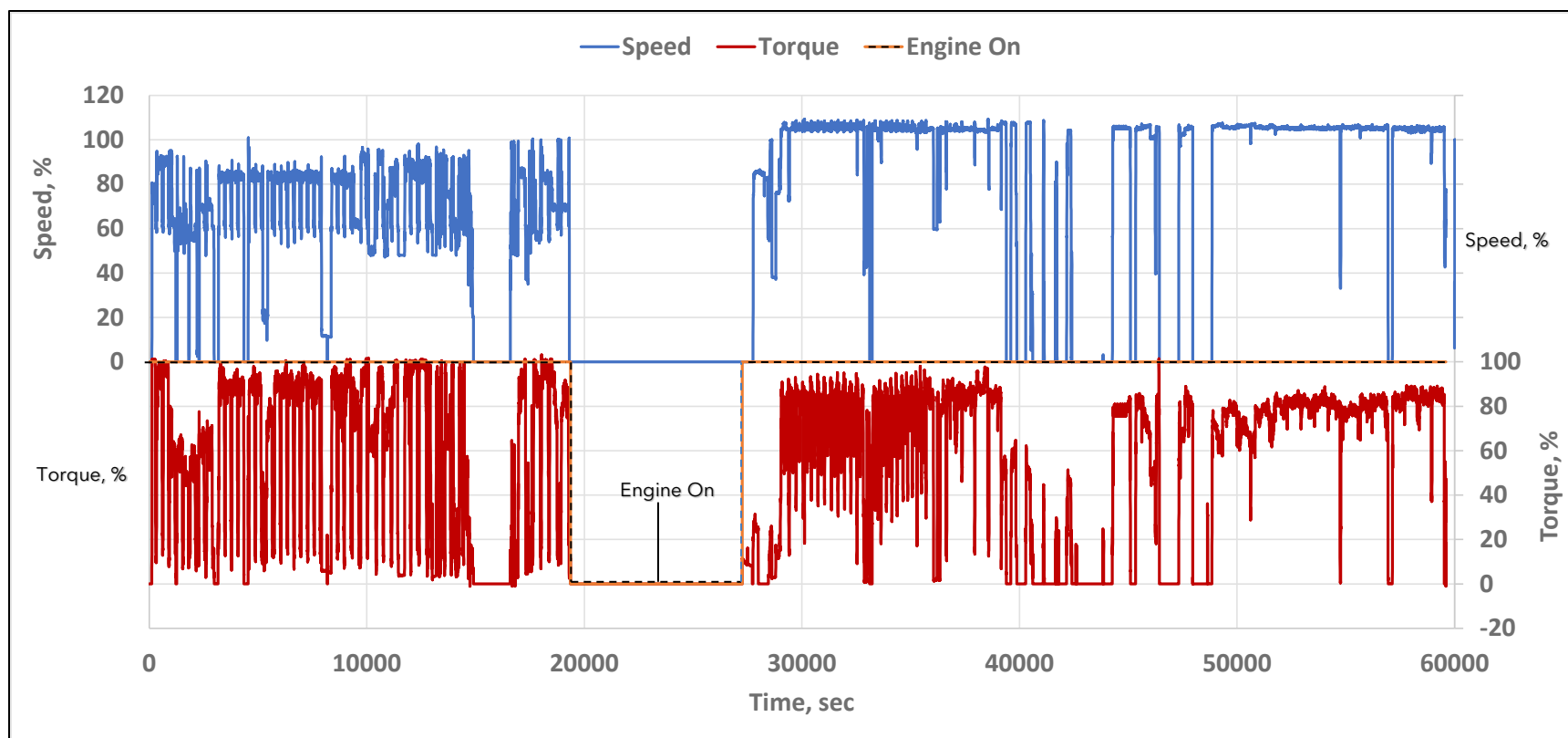
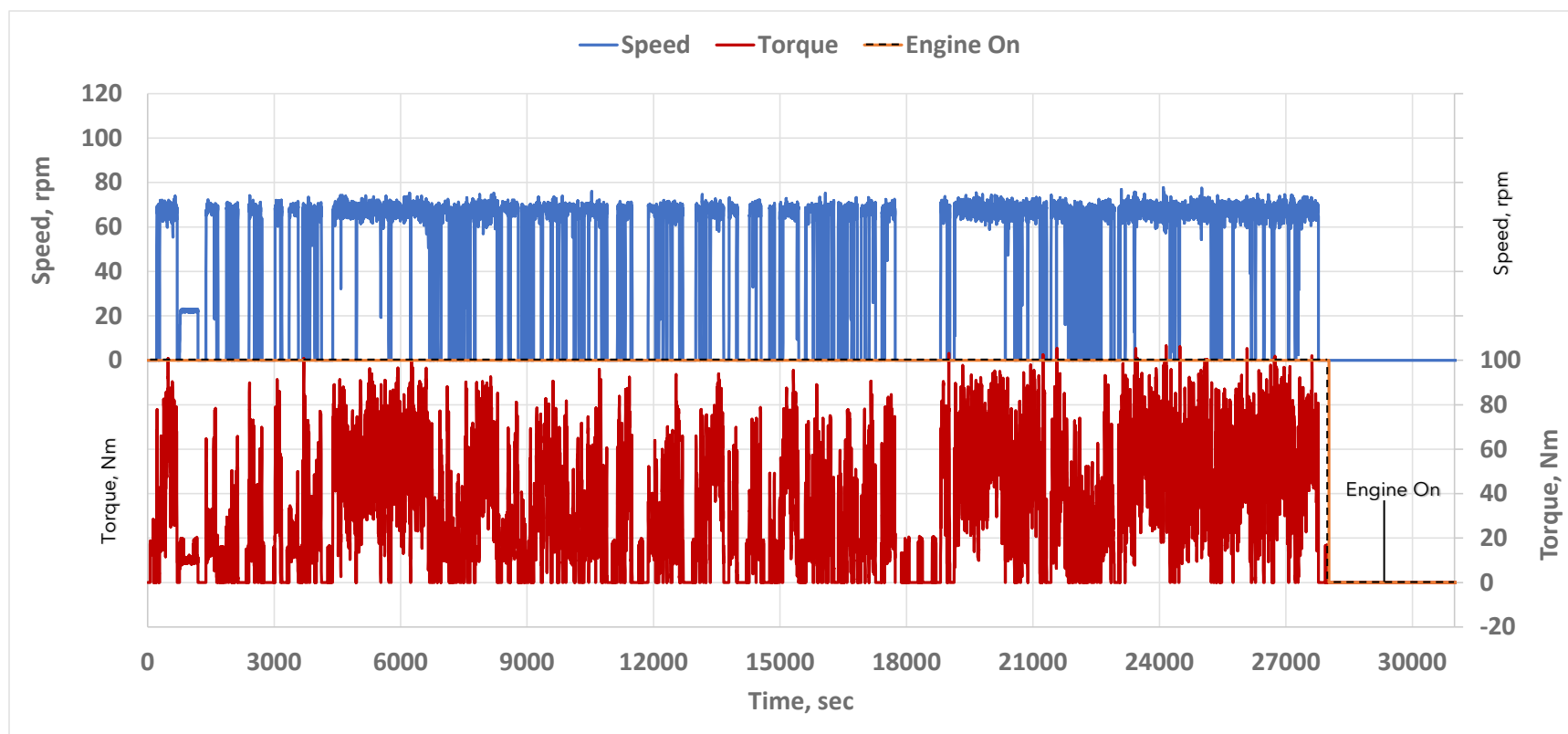
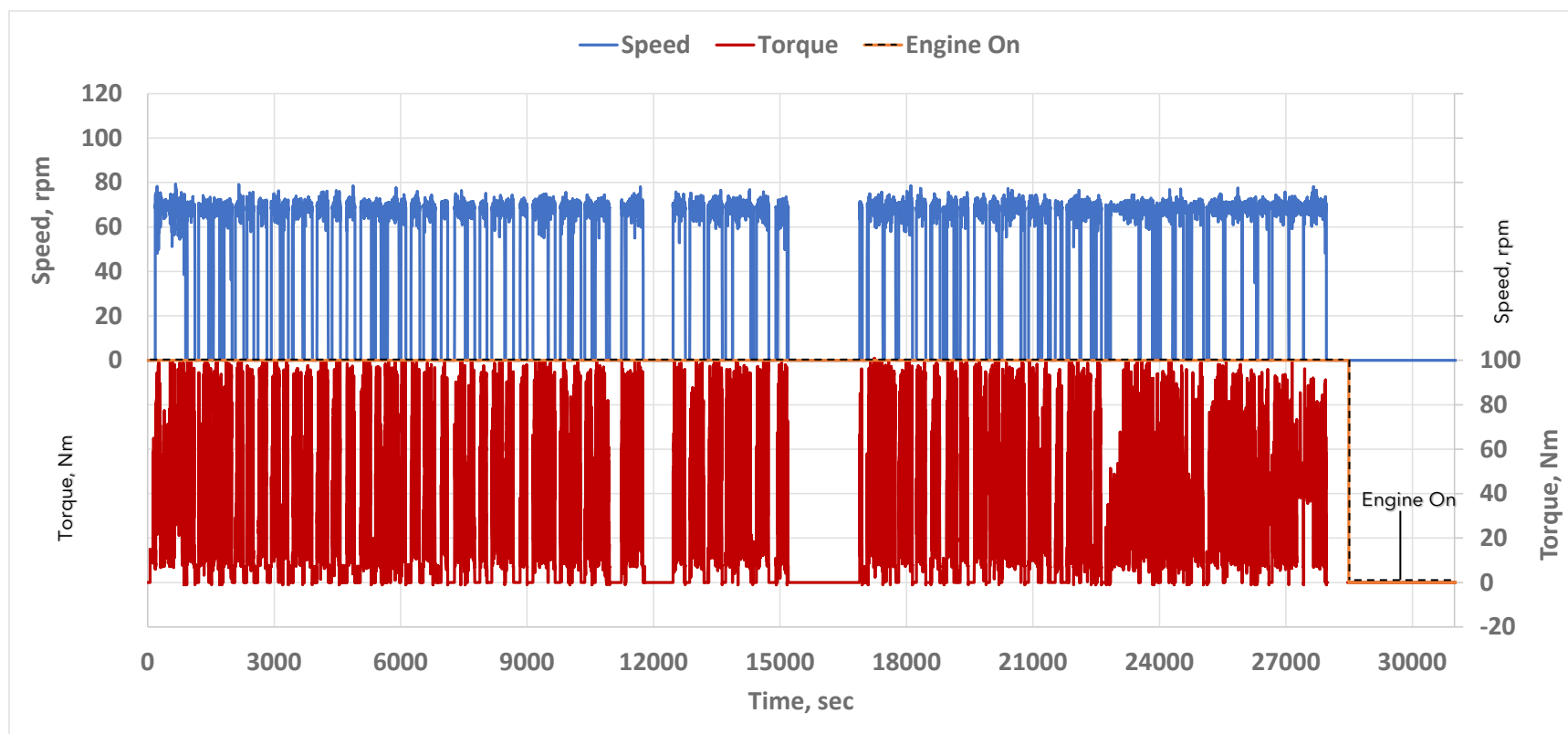


FIGURE 51. FIELD CYCLE 04 - AG TRACTOR - CUMMINS QSX15

**FIGURE 52. FIELD CYCLE 07 - AG TRACTOR - CUMMINS QSX15**

**FIGURE 53. FIELD CYCLE 09 - EXCAVATOR - CATERPILLAR C9.3**

**FIGURE 54. FIELD CYCLE 11 - EXCAVATOR - CATERPILLAR C9.3**

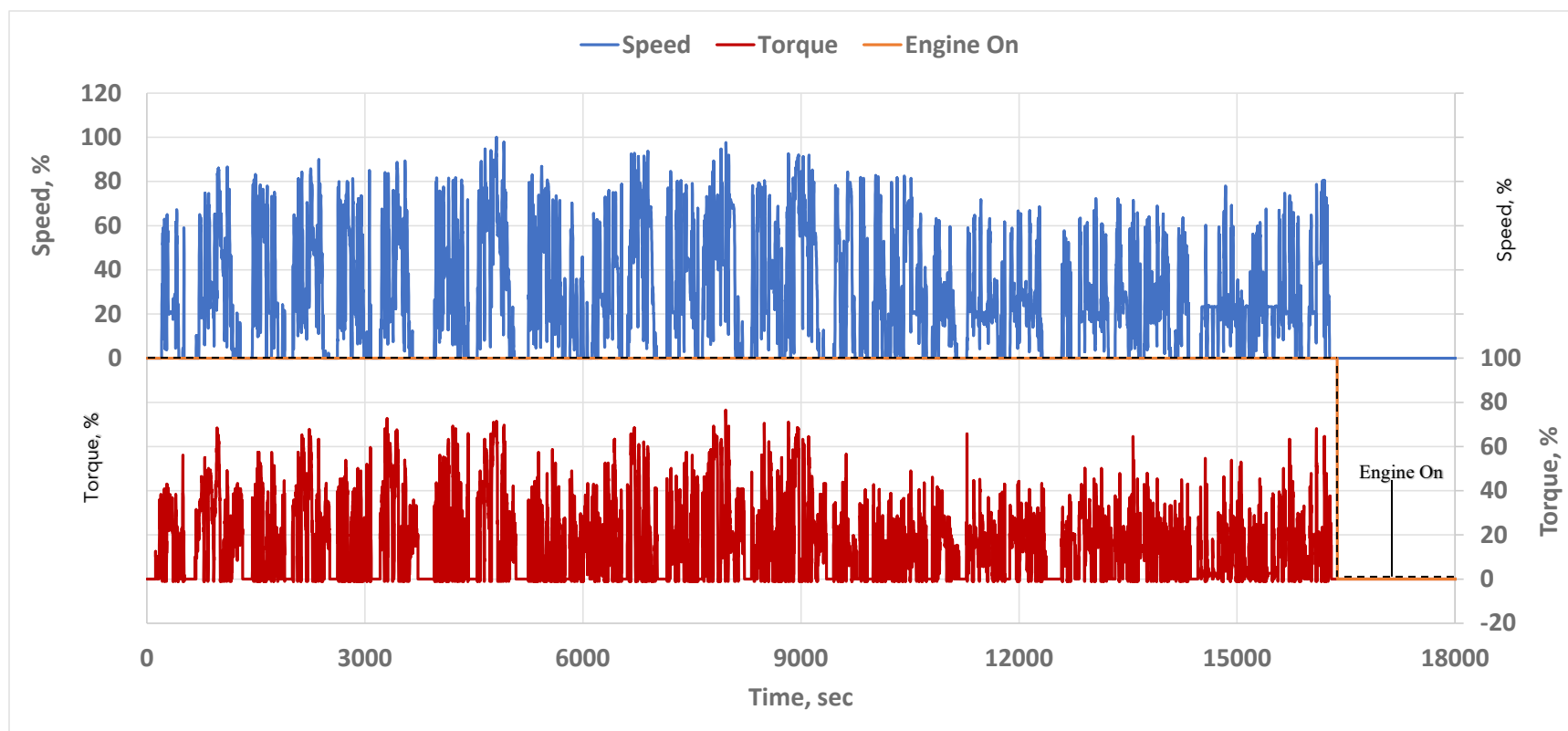


FIGURE 55. FIELD CYCLE 12 - YARD TRACTOR - CUMMINS QSB6.7

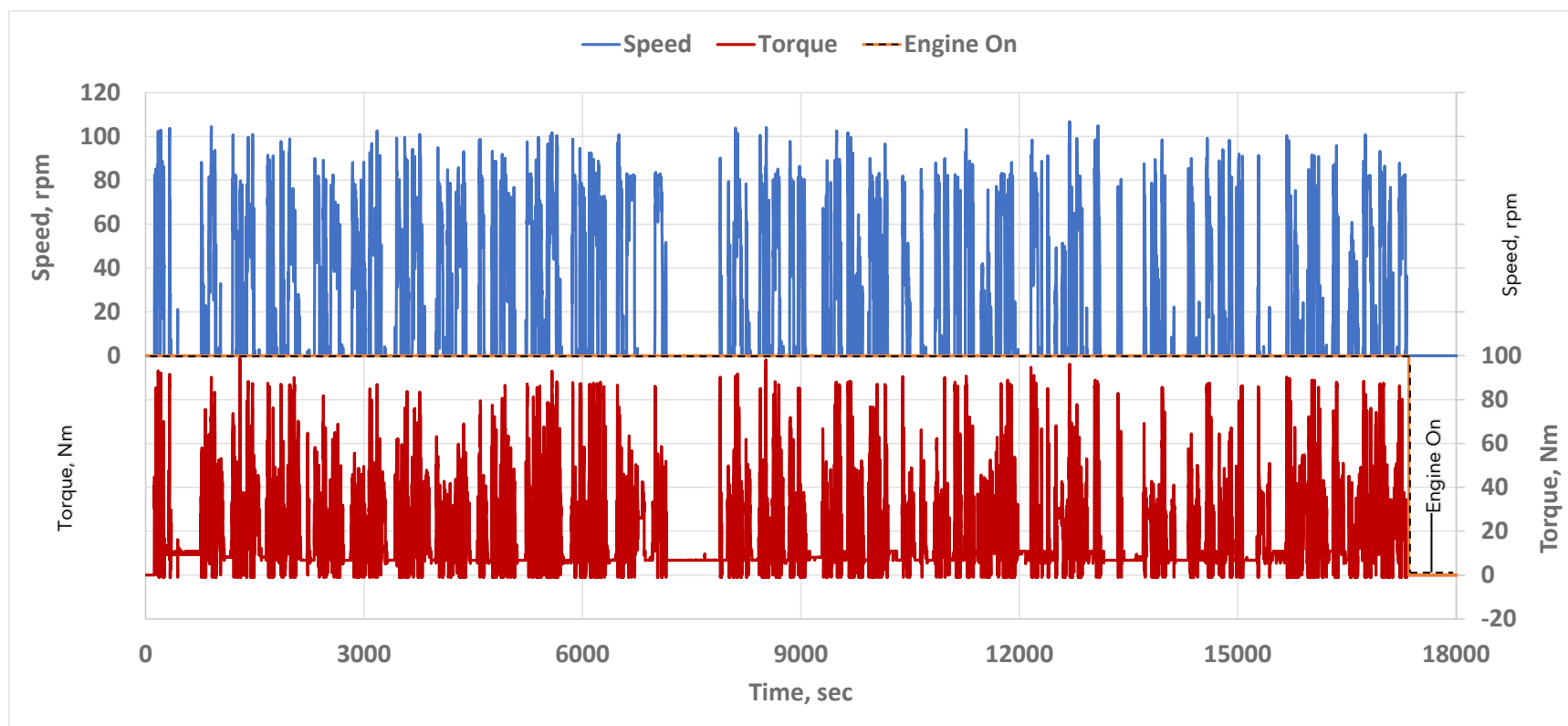


FIGURE 56. FIELD CYCLE 14 - TERMINAL TRACTOR - VOLVO D8