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CHARACTERIZATION OF FUEL IMPACTS ON HEAVY-DUTY LOW NOX ENGINE EMISSIONS

Final Report

July 2023

COORDINATING RESEARCH COUNCIL, INC.
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FINAL REPORT

Prepared for:

Coordinating Research Council (CRC)

CRC Contract RW-120
SwRI® Project Number 03.27185

Prepared by:

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POWERTRAIN ENGINEERING DIVISION

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Table **Page**

LIST OF ACRONYMS

2B-MAW	2-Bin Moving Average Window (for in-use emissions)
ACES	Advanced Collaborative Emissions Study
ASC	Ammonia Slip Catalyst
AT	Aftertreatment
BL	Baseline
BMEP	Brake Mean Effective Pressure
BSCO	Brake-Specific CO Emissions
BSFC	Brake-Specific Fuel Consumption
$BSNO_X$	Brake-Specific NO_X Emissions
BSPM	Brake-Specific PM Emissions
CA50	Crank Angle Location of 50 Percent Cumulative Heat Release
CAN	Controller Area Network
CARB	California Air Resources Board
CDA	Cylinder Deactivation
CFR	U.S. Code of Federal Regulations
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CRC	Coordinating Research Council
CSF	Catalyzed Soot Filter
DAAAC	Diesel Aftertreatment Accelerated Aging Cycles
DEF	Diesel Exhaust Fluid (32% urea by weight)
DOC	Diesel Oxidation Catalyst
dP	DPF Differential Pressure
DPF	Diesel Particulate Filter
EMA	Truck and Engine Manufacturers Association
EFH	Emissions over test cycle with regeneration (for UAF calculation)
EFL	Emissions over test cycle without regeneration (for UAF calculation)
EGR	Exhaust Gas Recirculation
EOL	End-of-Life (for emissions)
EPA	U.S. Environmental Protection Agency
EU-ISC	European Union In-Service Conformity Driving Route
FAME	Fatty Acid Methyl Ester
FTIR	Fourier Transform Infrared Analyzer
FTP	U.S. Heavy Duty Transient Federal Test Procedure
FUL	Full Useful Life
GHG	Greenhouse Gas

HC	Hydrocarbons
HHD	Heavy Heavy-Duty regulatory category
HT	High Temperature
HVO	Hydrogenated Vegetable Oil
IRAF	Infrequent Regeneration Adjustment Factor
LCFS	California Low Carbon Fuels Standard
LLC	Low Load Cycle
LO-SCR	Light Off SCR Catalyst
MHD	Medium Heavy-Duty regulatory category
MSS	AVL Micro Soot Sensor
MY	Model Year
NAAQS	National Ambient Air Quality Standard
NMHC	Non-Methane Hydrocarbons
N_2O	Nitrous Oxide
NO_X	Oxides of NitrogenPEMS Portable Emission Measurement System
PM	Particulate Matter
RMC	Ramped Modal Cycle
RMC-SET	Ramped Modal Cycle Supplemental Emission Test
SCR	Selective Catalytic Reduction (ammonia-based)
SwRI	Southwest Research Institute
SNTE	CARB Southern Not-to-Exceed In-Use Emission Test Driving Route
THC	Total Hydrocarbons
TP	Tailpipe
UAF	Upward Adjustment Factor (for Infrequent Regeneration)
ULSD	Ultra Low Sulfur Diesel
VGT	Variable Geometry Turbine
zCSF	Zone-coated Catalyzed Soot Filter

EXECUTIVE SUMMARY

In recent years, CARB and EPA have been working to put in place more stringent standards for NO_X emissions from a number of industry sectors, with on-highway heavy-duty trucks being a key target for further reductions in tailpipe NO_X. In support of this goal, both CARB and EPA have engaged SwRI in a series of technical demonstration programs to support the development of these new regulations. These programs have resulted in the development of the Stage 3 Low NO_X demonstration engine platform, which can produce tailpipe emission levels in the range of standards adopted by CARB and EPA.

An important part of understanding the capability for meeting Low NO_X standards is to understand the potential for different factors outside the engine itself to create variability in the tailpipe emissions. One important factor with the potential to create such variation is the fuel injected to the engine. Fuels can have both short-term and long-term impacts on the performance of the emission control system. For the purposes of this program, "short-term" refers to any impact from a fuel change which would become apparent as soon as the new fuel has substantially replaced any previous fuel in the engine fuel system. Long-term impacts from a fuel would be anything that would manifest over a long-period of time operating on a different fuel, such as an increase in aftertreatment deterioration rates. The program detailed in this report was designed to examine the short-term impacts of fuel variations on the performance of the emission control system from a representative Low NO_X engine. The fuels used in this program ranged from conventional diesel fuels with varying fuel properties, to various renewable fuels and fuel blends. The fuels were chosen to represent the kinds of fuels expected to be present in the market in 2027 and beyond (although many of these same fuels are already present today). A list of the nine (9) fuels used in this program is given below in Table 1, along with brief descriptions of each fuel. It should be noted that the properties of the fuels examined in this program fall within the limits of ASTM specifications, with the exception of the B50 biodiesel blend.

TABLE 1. TEST FUELS FOR CRC SHORT-TERM FUEL IMPACT TESTING ON LOW NO_X ENGINE

Test Fuel	Fuel Code	Fuel Description
0	2D	EPA 2D Certification Diesel Fuel
1	BL	Baseline CARB Reference Diesel (Low Aromatic)
2	Hi Arom Dsl	ULSD: Low Cetane, High Aromatics, 15ppm Sulfur, B5
3	Hi T90 Dsl	ULSD: High T90 (distillation), High Aromatics, 15ppm Sulfur , B5
4	B20	B20: Soy-derived biodiesel, without stability additives blended w/ high aromatics high T90 diesel, 15 ppm S
5	B50	B50: Soy-derived biodiesel, without stability additives blended w high aromatics high T90 diesel, 15 ppm S
6	B20R80	Renewable: B20 blended w/ renewable (20% Soy-derived biodiesel + 80% R100)
7	R50	Renewable: 50% R100 + 50% high aromatics high T90 diesel, 15 ppm S
8	R100	Renewable: R100, Low Density, High Cetane fuel

Two kinds of evaluations were conducted during this program. All fuels were examined for their impact on tailpipe criteria pollutant emissions (NO_X, PM, NMHC, CO) and GHG emissions (CO_2 and N_2O) using triplicate test sequences over the 2027 regulatory cycles for heavy-duty engines (the heavy-duty transient FTP, the steady-state RMC-SET, and the new LLC). In addition, three of the fuels were also evaluated to examine their impact on DPF regeneration frequency, which can impact Infrequent Regenerating Adjustment Factors (IRAF) that are included in the compliance assessment over the certification cycles.

A summary of the tailpipe emissions for the various test fuels evaluated is given below in Figure 1, for all of the regulatory cycles. For the high-load RMC-SET cycle, tailpipe emissions were unaffected by fuel differences. For the lower load FTP and LLC cycles, fuel effects were observed. Over the range of conventional diesel fuels tested, variations ranged from -2 to +4 mg/hp-hr on the FTP and -5 to +2 mg/hp-hr on the LLC, with higher aromatic content fuels generally having higher tailpipe NO_X emissions relative to lower aromatic content fuels. The various renewable diesel and renewable diesel blends, as well as biodiesel blends of up to 20% biodiesel content by volume (B20), all fell within this same range. This indicates no significant impact on tailpipe NO_X emission compliance for B20 and renewable diesel blends, although the renewable diesels did generally fall at the lower end of this range. There was no significant difference between the B20 blend and the base diesel fuel (Hi T90 diesel) that the blend was made from. The 50% biodiesel blend resulted in a larger increase in tailpipe NO_X emissions on the FTP and LLC cycles of 11 mg/hp-hr. This was due to a combination of increased engine-out NO_X and lower exhaust gas temperatures. All measured NO_X levels were below the 2027 EPA limit values, although the B50 was close to the limit on the FTP. No significant changes in tailpipe PM, HC, or CO emissions were observed for any of the fuels.

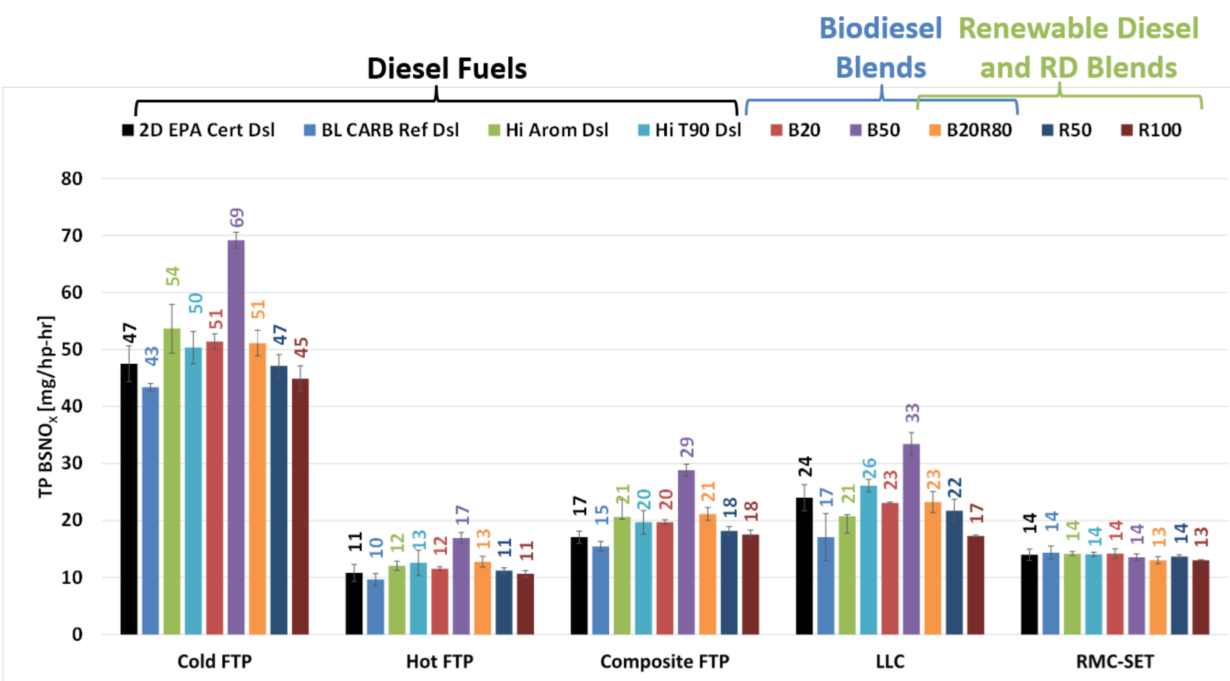

FIGURE 1. SUMMARY OF TAILPIPE NO_X EMISSIONS ON VARIOUS TEST FUELS

In terms of how these regulated emissions cycle results might translate to in-use emission impacts, an analysis was conducted based on these results and existing data available on field cycles for the Low NO_X engine. The result of this analysis is shown in Figure 2, showing the projected change in Bin 2 NO_X emissions compared to the EPA 2D Certification fuel.

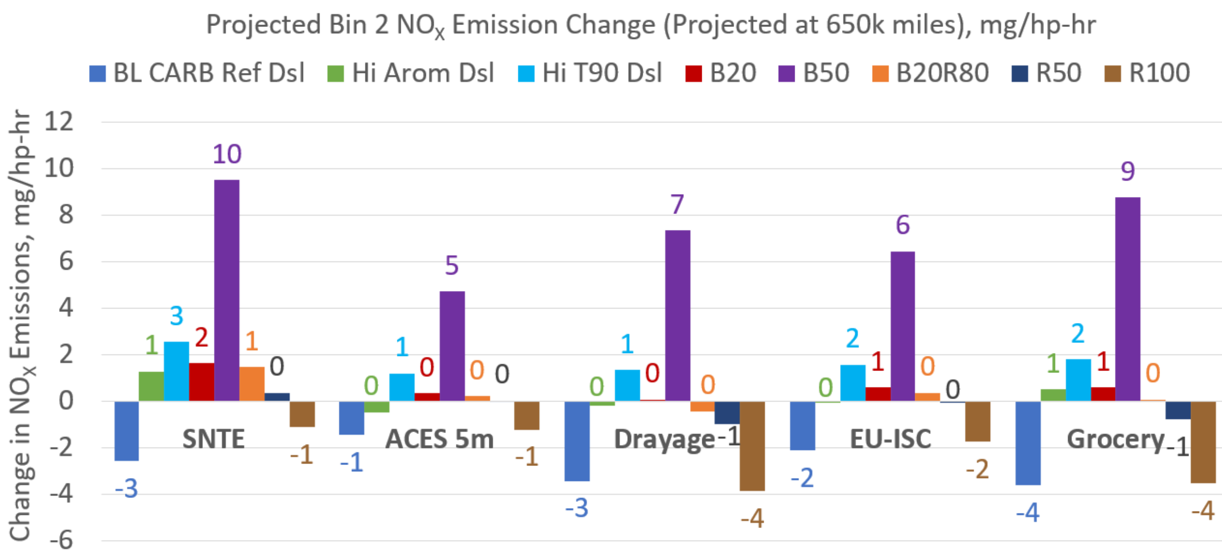

FIGURE 2. RELATIVE IMPACT OF DIFFERENT FUELS ON BIN 2 NO_X EMISSIONS ON VARIOUS FIELD CYCLES

The projections indicate tailpipe NO_X emission changes ranging from -4 to +3 mg/hp-hr for the various program conventional diesel fuels, while the renewable diesel fuels and blends are generally NO_X neutral or show an improvement in the case of R100 on lower load field cycles. For the higher aromatic level diesel fuels, this change in emissions is on the order of +5% of the off-cycle lab standard of 58 mg/hp-hr and +4% of the in-use standard of 73 mg/hp-hr. The B50 blend results indicate a significant increase in tailpipe NO_X of between 5 and 10 mg/hp-hr, depending on the cycle, which is on the order of 9 to 17% of the off-cycle lab standard and 7 to 14% of the in-use standard. It should be noted that these numbers represent the full range of potential impact from the range of fuels tested, and that actual fuel impacts will likely vary within that range.

Testing was also conducted to assess the impact of selected fuels on DPF soot accumulation and regeneration frequency. Figure 3 shows a comparison of soot accumulation rates for a B20 blend and the 100% renewable diesel (R100), in comparison to the baseline diesel fuel over the FTP cycle. This data indicated that soot load in DPF for either B20 or R100 was increasing at half the rate normally observed for the baseline fuel. This lower rate of accumulation would likely lead to less frequent need for active DPF regenerations on lower load cycles, which in turn could have beneficial effects on tailpipe NO_X through smaller regeneration adjustment factors, and lower fuel consumption due to fewer regenerations. There is also potential for improved aftertreatment durability due to less frequent high temperature exposure, although this would need to be verified with further testing.

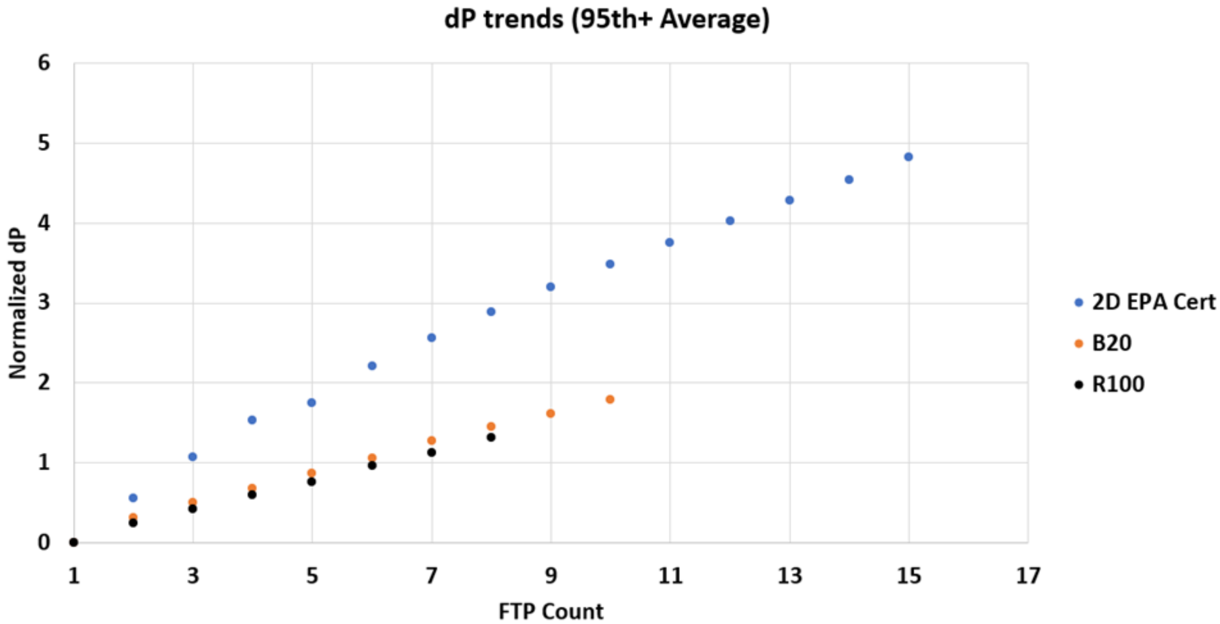

FIGURE 3. IMPACT OF SELECTED FUELS IN DPF SOOT ACCUMULATION AND DIFFERENTIAL PRESSURE

1.0 INTRODUCTION AND BACKROUND

This report details the test procedures and results from a test program that was run at Southwest Research Institute (SwRI) on behalf of the Coordinating Research Council (CRC). The objective of this program was to examine the short-term impact of various test fuels on the emission performance of the Stage 3 Low NO_X test article. For the purpose of this program, short-term impacts are defined as changes in engine or emissions performance which will be apparent as soon as the new fuel has made its way into the engine fuel system, or at most might be apparent within a few test cycles of running after a fuel change. In contrast long-term impacts can be defined as those which would manifest over long periods of operation, such as aftertreatment durability impacts, and these are out of the scope of the present work.

Despite decades of progress in improving emission controls and improving air quality, some parts of the U.S. continue to struggle to reach attainment with mandated National Ambient Air Quality Standards (NAAQS) for ground level ozone, for which NO_X emissions are a key precursor. As a result, in recent years CARB and EPA have been working to put in place more stringent standards for NO_X emissions from a number of industry sectors, with on-highway heavy-duty trucks being a key target sector for further reductions in tailpipe NO_X standards. In support of this goal, both CARB and EPA have engaged SwRI in a series of technical demonstration programs to support the development of these new regulations. These programs have resulted in the development of the Stage 3 Low NO_X demonstration engine platform, which can produce tailpipe emission levels in the range of standards adopted by CARB and EPA. The Stage 3 Low NO_X platform is described in more detail in the Methodology section of the report, and further details can be found in previous public references [1][2][3][4][5].

An important element influencing the capability to meet Low NO_X standards is the potential for non-engine-related factors to contribute to tailpipe emissions variability. One important factor with the potential to create such variation is the fuel injected to the engine, which can have both short-term and long-term impacts on the performance of the vehicle emission control systems. The focus of the program documented in this report is to examine the short-term performance impacts from fuel changes.

Pathways by which fuels might affect short-term emission control system performance could include:

- Changes in engine-out NO_X emission rates that could impact system performance, especially at low aftertreatment operating temperatures or during cold-start.
- Changes that could impact combustion stability during cold-start (this could result in the need to make calibration adjustments).
- Changes that impact the amount of available fuel energy (oxygenates, etc.) that could potentially change warm-up or thermal management characteristics.
- Changes that significantly impact engine-out HC emissions in a way that could alter $NO\text{-}NO_2$ oxidation rates.
- Changes that significantly alter soot production, so as to decrease or increase soot loading rates on the DPF (this impact could take more significant test time to completely characterize soot loading rate, but a preliminary assessment was made over a relatively short number of test days in the current research).

Working with CRC, SwRI developed a test matrix that would utilize the Stage 3 test platform to examine the short-term impact of a variety of different test fuels on the emission control system performance. Two different types of test were conducted:

- The first test approach was to run emission test sequences similar to those used to document the emissions of the Stage 3 engine during the demonstration program itself. These test sequences involved the standard regulatory cycles planned for MY 2027 heavy duty engines, including the heavy-duty transient FTP, the steady-state RMC-SET, and the newly developed Low Load Cycle (LLC). This would allow examination of any potential direct impacts on tailpipe emissions from the candidate fuels in question. A total of seven (7) candidate fuels were examined in this test matrix, in comparison to a CARB reference diesel fuel and an EPA 2D certification diesel fuel.

- The second test approach was to examine the impact of fuel changes on passive soot oxidation over the DPF, and therefore on the frequency of active regeneration. This has an indirect impact on tailpipe emissions which is documented using an Upward Adjustment Factor (UAF), which is applied to the emission levels from compliance results generated using the regulatory cycles discussed above. Therefore, if a fuel causes a significant change in regeneration frequency, this could impact emission compliance. This testing involved running a sequence of 12 successive hot-start FTP tests, with the usual 20-minute engine off soak between tests. This allowed monitoring of DPF differential pressure and soot loading rates. If a significant difference was noted for a given fuel, the data were used to revise the calculation of regeneration frequency and the UAF. Only a limited number of fuels, in particular those that were projected to have a significant potential impact on engine-out soot levels, were examined in this way.

More details on the test methodology for both experiments are given below on the Methodology section of the report.

The test fuels were chosen by CRC with significant input from the members of the Truck and Engine Manufacturers Association (EMA). The test fuels represent a wide variety of fuel properties and feedstocks that are expected to be present in the marketplace in the 2027 timeframe. Renewable fuels such as biodiesel (B) and renewable diesel (R) fuel were examined in varying blends with each other or with selected high T90 conventional diesel fuels. Such renewable fuels and blends are already common in California markets as a result of the Low Carbon Fuel Standard (LCFS), and these fuels are expected to become much more broadly used outside California as part of the societal goal to decarbonize transportation. More details on the individual test fuels and their properties are given below in the Methodology section of the report.

2.0 METHODOLOGY AND MATERIALS

2.1 Stage 3 Test Engine and Emission Control System

The test article used for the fuel evaluations was the Stage 3 Low NO_X demonstration engine, which was developed at SwRI. The key parts of Stage 3 emission control system are depicted in Figure 4 below. The system consists of three key large scale components:

- A modified 2017 Cummins X15 engine with an updated calibration
- Cylinder deactivation (CDA) added to the engine via Eaton hardware
- A dual-SCR, dual DEF dosing aftertreatment system

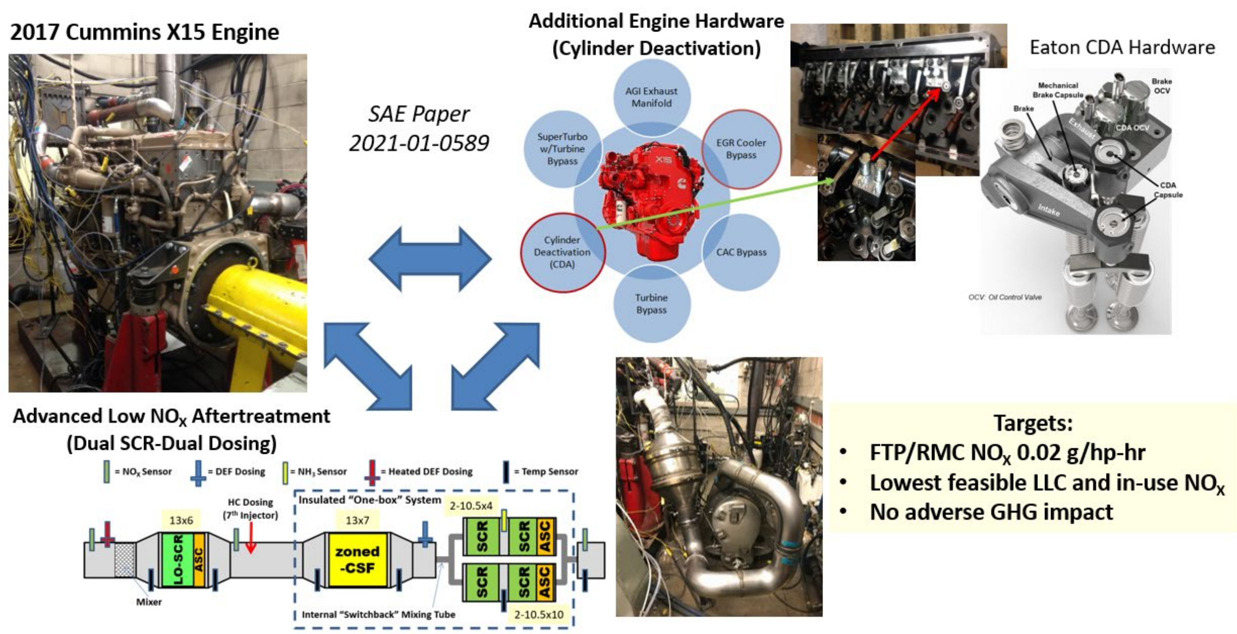

FIGURE 4. THE STAGE3 LOW NO_X EMISSION CONTROL SYSTEM

Each of these components is described in more detail below. The system was managed by an integrated control system developed by SwRI that incorporated modified engine calibrations, an integrated multi-mode thermal management strategy, and a multi-bed, model-based diesel exhaust fluid (DEF) dosing control architecture incorporating short-term and long-term feedback elements. The control system concept is illustrated in Figure 5.

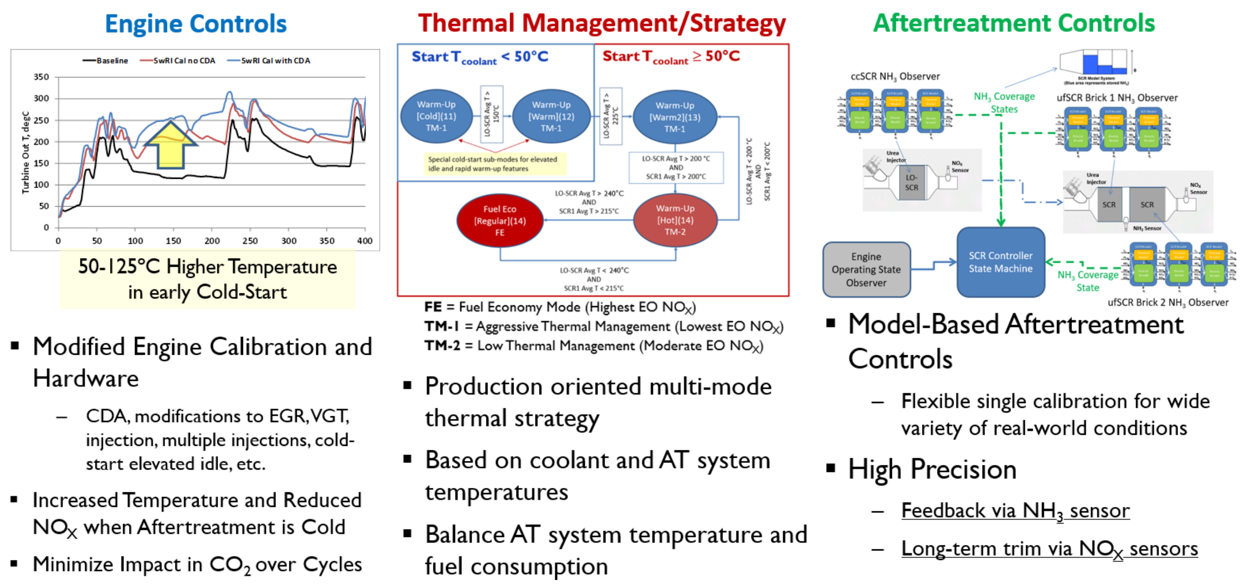

FIGURE 5. STAGE 3 LOW NO_X INTEGRATED CONTROL SYSTEM

2.1.1 Stage 3 Test Engine with CDA

The test engine for this program was a modified production 2017 Cummins X15 Efficiency Series engine. The engine is shown in Figure 6, installed in a transient emission test cell at SwRI. The engine selected for this program was calibrated at a nominal 500 hp maximum power rating at 1800 rpm. It was supplied to the program by Cummins, along with the stock aftertreatment system, although that system was not utilized for this program. A summary of some basic engine parameters for this test engine is given in Table 2 below.

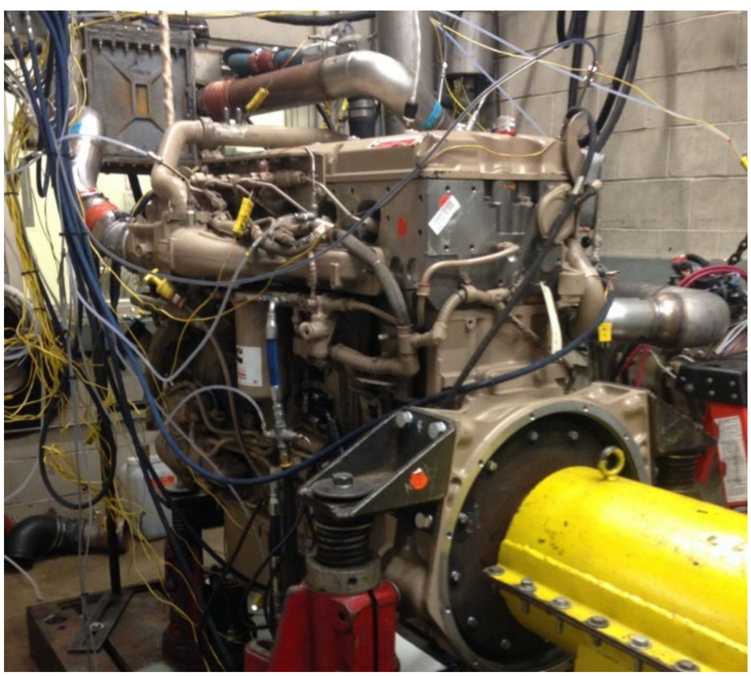

FIGURE 6. 2017 MY CUMMINS X15 ENGINE

TABLE 2. CUMMINS X15 ENGINE PARAMETERS

Parameter	Value
Configuration	Inline 6 cylinder
Bore x Stroke	137 x 169 mm
Displacement	15.0 L
Rated Power	373 kW (500 hp)
Rated Speed	1800 rpm
Peak Torque	2500 Nm
Peak Torque Speed	1000 rpm

The engine was an inline 6-cylinder diesel engine that was turbocharged and intercooled, with a single stage turbocharger featuring a variable geometry turbine (VGT). 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 engine did feature an asymmetric exhaust manifold design, wherein the front three cylinders were primarily responsible for driving EGR flow through the cooler. 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. However, for the Stage 3 engine, active regeneration of the filter was accomplished using in-exhaust injection, due to concerns about the potential impact of post-injected hydrocarbons on the durability of the LO-SCR catalyst.

The cylinder deactivation system was a key addition to the engine hardware that helped to enable meeting Low NO_X emission targets while at the same time avoiding any increase in GHG emissions. The CDA hardware was supplied by Eaton, and it enabled independent deactivation of any or all cylinders, allowing for a flexible strategy to maximize benefits while at the same time avoiding vibration issues. CDA is always used below 3bar BMEP because it provides both fuel consumption and thermal management benefits. An example of the CDA strategy for the warmed-up engine mode is given in Figure 7 below.

		BMEP [bar]					
		Motoring	0	1	2	3	4
Ne [RPM]	600	3B	3B	3B	6CF	6CF	6CF
	700	3B	3B	3B	3B	6CF	6CF
	800	3B	3B	3B	3B	6CF	6CF
	900	3B	3B	3B	3B	3B	6CF
	1000	3B	2A	2A	3B	3B	6CF
	1100	1D	2A	2A	3B	3B	6CF
	1200	1D	2A	2A	4A	4A	6CF
	1300	1D	2A	2A	4A	4A	6CF
	1400	1D	2A	2A	4A	4A	6CF
	1500	1D	2A	2A	4A	4A	6CF
	1600	1D	2A	2A	4A	4A	6CF
	1700	1D	2A	2A	4A	4A	6CF
	1800	6CF	6CF	6CF	6CF	6CF	6CF
	1900	6CF	6CF	6CF	6CF	6CF	6CF

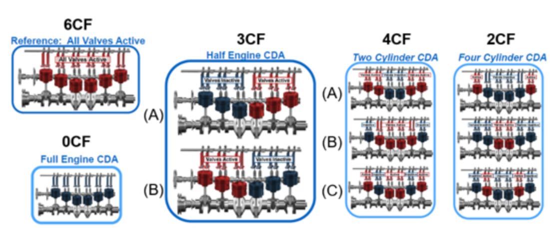

FIGURE 7. EXAMPLE OF CDA STRATEGY – WARMED-UP ENGINE MODE

2.1.2 Stage 3 Low NO_X Aftertreatment System

The aftertreatment system used for this testing was the final Stage 3 configuration as shown below in Figure 8. For this work, the Development Aged parts were utilized, and these parts were hydrothermally aged to represent 435,000 miles of equivalent aging. These parts were also used for a variety of development and testing tasks while the Final Aged system was being aged or used for another purpose.

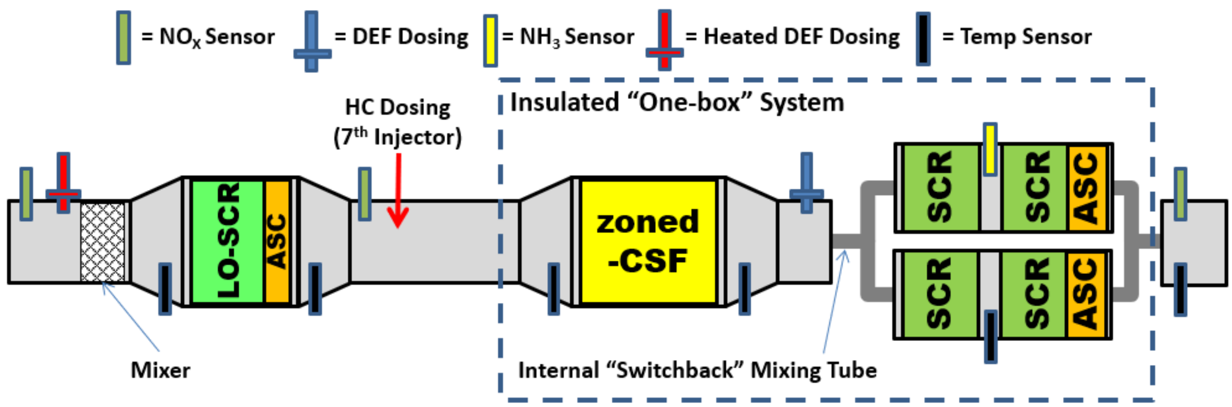

FIGURE 8. STAGE 3 LOW NO_X AFTERTREATMENT SYSTEM

A summary of the tailpipe NO_X performance of the Stage 3 Low NO_X system over multiple test events conducted during the previous demonstration program is shown below in Table 3. As can be seen, the emission levels are representative of levels that might be expected from a test article compliant with a 20 mg/hp-hr NO_X standard at 435,000 miles. In addition, as can be seen the system performance has been quite stable over an extended period of time, therefore the Development Aged system was a good candidate for the fuels evaluations. It should be noted that all of these results except the last one in bold were generated using an 2D Certification grade diesel fuel that met EPA specifications given in 40 CFR Part 1065.

TABLE 3. STAGE 3 DEVELOPMENT AGED PART PERFORMANCE ON TRANSIENT FTP CYCLES OVER TIME

Date	Tailpipe $BSNO_X$, g/hp-hr				
	Cold	Hot 1	Hot 2	Hot 3	Composite
6/19/2020	0.050	0.009	0.009	0.010	0.015
7/15/2020	0.048	0.010	0.009	0.009	0.015
11/18/2020	0.049	0.010	0.010	n/a	0.016
10/21/2021	0.055	0.007	n/a	n/a	0.014
4/22/2022	0.046	0.008	n/a	n/a	0.013
12/11/2022	0.048	0.011	0.011	0.010	0.016
12/12/2022	**0.043**	**0.011**	**0.009**	**0.010**	**0.016**

Performance check on 2D Cert Fuel

Baseline run on CRC BL Fuel

2.2 Test Fuels

The selection of the test fuel matrix was made by the CRC advisory group that managed this program, with a significant amount of input from the members of EMA. A list of the final set of test fuels is given below, shown in the desired test order.

TABLE 4. SUMMARY LIST OF TEST FUELS

Test Fuel	Fuel Code	Fuel Description
0	2D	EPA 2D Certification Diesel Fuel
1	BL	Baseline CARB Reference Diesel (Low Aromatic)
2	High Arom Dsl	ULSD: Low Cetane, High Aromatics, 15ppm Sulfur, B5
3	High T90 Dsl	ULSD: Hi T90 (distillation), High Aromatics, 15ppm Sulfur , B5
4	B20	B20: Soy-derived biodiesel, without stability additives blended w/ high aromatics high T90 diesel, 15 ppm S
5	B50	B50: Soy-derived biodiesel, without stability additives blended w high aromatics high T90 diesel, 15 ppm S
6	B20R80	Renewable: B20 blended w/ renewable (20% Soy-derived biodiesel + 80% R100)
7	R50	Renewable: 50% R100 + 50% high aromatics high T90 diesel, 15 ppm S
8	R100	Renewable: R100, Low Density, High Cetane fuel

An abbreviated comparison of the key target characteristics for each test fuel are given below in Table 5. More detailed descriptions of target characteristics for the desired test fuels, and reasoning behind those choices, are shown below in Table 6 for the conventional ULSD fuels, Table 7 for the Biodiesel blended fuels, and Table 8 for the Renewable Diesel blended fuels, respectively.

TABLE 5. COMPARISON OF KEY TEST FUEL PROPERTY TARGET RANGES

Fuel	1	2	3	4	5	6	7	BL
Fuel Description	B20 High T90 Base	ULSD High Aromatics	B50 High T90 Base	ULSD High T90 HA	B20/R80	R50 High T90 Base	R100	CARB ULSD
FAME content vol%	18 - 20	4 - 6	48 - 52	4 - 6	18 - 22	0	0	0
Renewable Diesel Content, vol%	0	0	0	0	78 - 82	48 - 50	> 98	0
Cetane Number, min	report	40 - 42	report	45 - 48	report	report	80 - 90	50 - 55
Aromatic content, total vol%	report	32 - 35	report	32 - 35	< 5	16 - 18	< 5	8 - 10
Paraffinic, vol%	report	report	report	report	report	report	> 95	report
Distillation T90, max °C	282 - 338	280 - 310	report	320 - 338	report	report	report	282 - 338
Stability, hrs (Rancimat)	6 - 10	n/a	> 6	n/a	> 6	n/a	n/a	n/a
Density, kg/m3	815 - 840	820 - 860	815 - 840	820 - 860	report	report	765 - 780	820 - 860

TABLE 6. TARGET TEST FUEL CHARACTERISTICS FOR ULSD FUELS

Fuel	Main Properties (**bold** = target concern)	ASTM D 975	Target range	Impacts
BASELINE: CARB Cert Diesel Selected as low emissions ULSD Reference fuel. Also, selected for Regeneration Testing as reference.	FAME content vol%	0-5%	0	CARB Cert Diesel is not expected to contain FAME
	Cetane Number, min	>40	50 - 55	CARB Diesel Cetane is commonly > 50
	Distillation T90, max °C	282 - 338	282 - 338	Typical range for diesel fuel
	Aromatic content, total vol%	<u><</u>35%	8 to 10	Closer to max level of 10 vol% allowed in the CARB diesel
	Aromatic content, heterocyclic		to report	Higher % of hetrocyclic can impact PM emissions
	Paraffinic, vol%		to report	
	Stability, minutes (Petrooxy Test)	None	to report	Expect to be 40 to 50 minutes which is typical range for diesel fuel
	Density, kg/m3		820 to 860	
	Viscosity, mm2/sec	1.9 - 4.1	1.9 - 4.1	
	Ash, max mass %	<u><</u>0.01	0.008 to 0.010	
	Sulfur, max mg/l	<u><</u>15 max	14 to 15	At limit levels allowed in the fuel standard to determine worst case impact
	Na + K, ppm	None	undetectable to < 1 ppm	At these levels no impact is expected on short term emissions
	Mg + Ca, ppm	None	undetectable to < 1 ppm	At these levels no impact is expected on short term emissions
	P, ppm	None	undetectable to < 1 ppm	At these levels no impact is expected on short term emissions
Fuel	**Main Properties (bold** = target concern)	**ASTM D 975**	**Target range**	**Impacts**
Low Cetane, High Aromatics, 15ppm Sulfur, B5 Selected as limit fuel for higher NOx and PM emissions Also, selected for Regeneration Testing as representative limit real world fuel	FAME content vol%	0-5%	4-6%	Close to maximum FAME allowed in Diesel and meet ASTM D6751. Can impact NOx, PM
	Cetane Number, min	>40	40 to 42	Low range available in the market place.
	Distillation T90, max °C	282 - 338	282 TO 310	Closer to lower range allowed in diesel fuel
	Aromatic content, total vol%	<u><</u>35%	32 to 35	Closer to max level allowed in diesel fuel
	Aromatic content, heterocyclic		to report	Higher % of hetrocyclic can impact PM emissions
	Paraffinic, vol%		to report	
	Stability, minutes (Petrooxy Test)	None	to report	Expect to be 40 to 50 minutes which is typical range for diesel fuel
	Density, kg/m3		820 to 860	
	Viscosity, mm2/sec	1.9 - 4.1	1.9 - 4.1	
	Ash, max mass %	<u><</u>0.01	0.008 to 0.010	At limit levels allowed in the fuel standard to determine worst case impact
	Sulfur, max mg/l	<u><</u>15 max	14 to 15	At limit levels allowed in the fuel standard to determine worst case impact
	Na + K, ppm	None	undetectable to < 1 ppm	At these levels no impact is expected on short term emissions
	Mg + Ca, ppm	None	undetectable to < 1 ppm	At these levels no impact is expected on short term emissions
	P, ppm	None	undetectable to < 1 ppm	At these levels no impact is expected on short term emissions
Fuel	**Main Properties (bold** = target concern)	**ASTM D 975**	**Target range**	**Impacts**
Hi T90, High Aromatics, 15ppm Sulfur , B5 Selected as limit fuel for higher PM and possibly NOx emissions independent of low Cetane influence Also, selected for Regeneration Testing as representative limit real world fuel	FAME content, vol%	0-5%	4-6%	Close to maximum FAME allowed in Diesel and meet ASTM D6751. Can impact NOx, PM
	Cetane Number, min	>40	45 to 48	Closer to average Cetane for US fuels
	Distillation T90, max °C	282 - 338	320 to 338	Closer to higher range allowed in D975
	Aromatic content, total vol%	<u><</u>35%	32 to 35	Closer to max level allowed in diesel fuel
	Aromatic content, heterocyclic			
	Paraffinic, vol%			
	Stability, minutes (Petrooxy Test)	None	to report	Expect to be 40 to 50 minutes which is typical range for diesel fuel
	Density, kg/m3		815 to 840 / 820 to 860	
	Viscosity, mm2/sec	1.9 - 4.1	1.9 - 4.1	
	Ash, max mass %	<u><</u>0.01	0.008 to 0.010	At limit levels allowed in the fuel standard to determine worst case impact
	Sulfur, max mg/l	<u><</u>15 max	14 to 15	At limit levels allowed in the fuel standard to determine worst case impact
	Na + K, ppm	None	undetectable to < 1 ppm	At these levels no impact is expected on short term emissions
	Mg + Ca, ppm	None	undetectable to < 1 ppm	At these levels no impact is expected on short term emissions
	P, ppm	None	undetectable to < 1 ppm	At these levels no impact is expected on short term emissions

TABLE 7. TARGET TEST FUEL CHARACTERISTICS FOR BIODIESEL BLENDED FUELS

Fuel	Main Properties (**bold** = target concern)	D 975	Target range	Impacts
B20, Soy-derived biodiesel, without stability additives blended with high aromatics high T90 diesel, 15 ppm S. Selected for higher PM and possibly NOx emissions with effects confounded by use of biodiesel with high level of unsaturation to represent limit B20 fuel.	FAME content vol%		18 to 20	Closer to maximum FAME allowed in Diesel w soy based biodiesel without stability additives to impact NOx emissions
	Cetane Number, min	>40	to report	Closer to average Cetane for US fuels
	Distillation T90, max °C	282 - 338	320 to 338	Closer to higher range allowed in D975
	Aromatic content, total vol%	≤35%	to report	
	Aromatic content, heterocyclic		to report	
	Paraffinic, vol%		to report	
	Stability, hrs (Rancimat)	None	> 6 to 10 hours	B20 blend from soy-derived biodiesel without additives is expected to be in this range
	Density, kg/m3		815 to 840 / 820 to 860	B20 blend from soy-derived biodiesel without additives is expected to be in this range
	Viscosity, mm2/sec	1.9 - 4.1	1.9 - 4.1	B20 blend from soy-derived biodiesel without additives is expected to be in this range
	Ash, max mass %	≤0.01	0.008 to 0.010	At limit levels allowed in the fuel standard to determine worst case impact
	sulfur, max mg/l	≤15 max	14 to 15	At limit levels allowed in the fuel standard to determine worst case impact
	Na + K, ppm	None	undetectable to < 1 ppm	At these levels no impact is expected on short term emissions
	Mg + Ca, ppm	None	undetectable to < 1 ppm	At these levels no impact is expected on short term emissions
	P, ppm	None	undetectable to < 1 ppm	At these levels no impact is expected on short term emissions

Fuel	Main Properties (**bold** = target concern)	D 975	Target range	Impacts
B50, Soy-derived biodiesel, without stability additives (unless needed), blended with high aromatics high T90 diesel, 15 ppm S Selected as limit Biodiesel blend for future if higher biodiesel mandate (>B20) becomes a reality	FAME content vol%		48 to 52	Closer to maximum FAME content likely to be seen in US marketplace
	Cetane Number, min	>40	to report	Closer to average Cetane for US fuels
	Distillation T90, max °C	282 - 338	to report	Closer to higher range allowed in D975
	Aromatic content, total vol%	≤35%	to report	
	Aromatic content, heterocyclic		to report	Higher % of hetrocyclic can impact PM emissions
	Paraffinic, vol%		to report	
	Stability, hrs (Rancimat)	None	> 6	Additives are allowed to meet minimum stability standard for biodiesel blends up to B20
	Density, kg/m3		815 to 840 / 820 to 860	
	Viscosity, mm2/sec	1.9 - 4.1	1.9 - 4.1	
	Ash, max mass %	≤0.01	to report	At limit levels allowed in the fuel standard to determine worst case impact
	sulfur, max mg/l	≤15 max	to report	At limit levels allowed in the fuel standard to determine worst case impact
	Na + K, ppm	None	undetectable to < 1 ppm	At these levels no impact is expected on short term emissions
	Mg + Ca, ppm	None	undetectable to < 1 ppm	At these levels no impact is expected on short term emissions
	P, ppm	None	undetectable to < 1 ppm	At these levels no impact is expected on short term emissions

TABLE 8. TARGET TEST FUEL CHARACTERISTICS FOR RENEWABLE DIESEL BLENDED FUELS (HVO-DERIVED)

Fuel	Main Properties (**bold** = target concern)	D 975	Target range	Impacts
R100, Low Density, High Cetane fuel Selected as R100 formulation to be found in the market	FAME content, vol%		0	
	Renewable Diesel Content, vol%		>98%	
	Cetane Number, min	>40	80 to 90	Very high Cetane, can impact NOx and PM emissions
	Distillation T90, max °C	282 - 338	to report	
	Aromatic content, total	≤35%	< 5	NOx; PM, DPF differential pressure & regeneration
	Aromatic content, heterocyclic			
	Paraffinic, vol%		> 95	
	Stability, minutes (Petrooxy)		> 50 minutes	
	Density, kg/m3		765 to 780	Low density can impact fuel economy and engine spray pattern
	Viscosity, mm2/sec	1.9 - 4.1	2 - 4.5	
	Ash, max mass %		0.008 to 0.010	Often see high ash with B5, lean toward high end of spec if possible
	sulfur, max mg/l	≤0.01	to report	This fuel is expected to have negligible or no sulfur
	Na + K, ppm	≤15 max	undetectable to < 1 ppm	At these levels no impact is expected on short term emissions
	Mg + Ca, ppm		undetectable to < 1 ppm	At these levels no impact is expected on short term emissions
	P, ppm		undetectable to < 1 ppm	At these levels no impact is expected on short term emissions

Fuel	Main Properties (**bold** = target concern)	D 975	Target range	Impacts
B20 blend (20% Soy-derived biodiesel + 80% R100 Selected to represent biomass-based diesel blend combining synergistic properties of biodiesel and renewable diesel. Currently available in the market	FAME content, vol%		18 to 22	
	Renewable Diesel Content, vol%		78 to 82	
	Cetane Number, min	>40	to report	Expect high Cetane, can impact NOx and PM emissions
	Distillation T90, max °C	282 - 338	to report	
	Aromatic content, total	≤35%	< 5	NOx; PM, DPF differential pressure & regeneration
	Aromatic content, heterocyclic			
	Paraffinic, vol%		to report	
	Stability, hrs(Rancimat)		> 6	
	Density, kg/m3		to report	Low density can impact fuel economy and engine spray pattern
	Viscosity, mm2/sec	1.9 - 4.1	2 - 4.5	
	Ash, max mass %		0.008 to 0.010	Often see high ash with B5, lean toward high end of spec if possible
	sulfur, max mg/l	≤0.01	to report	Often see high ash with B5, lean toward high end of spec if possible
	Na + K, ppm	≤15 max	undetectable to < 1 ppm	At these levels no impact is expected on short term emissions
	Mg + Ca, ppm		undetectable to < 1 ppm	At these levels no impact is expected on short term emissions
	P, ppm		undetectable to < 1 ppm	At these levels no impact is expected on short term emissions

Fuel	Main Properties (**bold** = target concern)	D 975	Target range	Impacts
R50 blend (50% R100 + 50% high aromatics high T90 diesel, 15 ppm S) Selected to represent blend of R with ULSD	FAME content, vol%		**0**	
	Renewable Diesel Content, vol%		48% - 50 %	
	Cetane Number, min	>40	to report	
	Distillation T90, max °C	282 - 338	to report	
	Aromatic content, total	≤35%	~ 16 % to 18 %	
	Aromatic content, heterocyclic			
	Paraffinic, vol%		to report	
	Stability, minutes (Petrooxy)		> 50 minutes	
	Density, kg/m3		to report	
	Viscosity, mm2/sec	1.9 - 4.1	2 - 4.5	
	Ash, max mass %		0.008 to 0.010	
	sulfur, max mg/l	≤0.01	to report	
	Na + K, ppm	≤15 max	undetectable to < 1 ppm	
	Mg + Ca, ppm		undetectable to < 1 ppm	
	P, ppm		undetectable to < 1 ppm	

The test fuels were procured from a variety of different sources, and CRC contracted with SwRI to handle the procurement of renewable materials and the production of some of the blends. The ULSD fuels were obtained from Gage Products Company. Detailed fuel property analytical results are given in Appendix A.

SwRI contracted with a diesel fuel supplier in the California market to acquire the following two commercially available renewable diesel fuels:

- 270 gallons of 100% renewable diesel (R100) that came from Hydrogenated Vegetable Oil (HVO) assigned SwRI fuel code CDF-11267.
- 216 gallons of R80/B20 which is a blend of 80% Renewable Diesel and 20% Biodiesel assigned SwRI fuel code CDF-11268.

These renewable fuels were acquired from a commercial supplier in California, and were acquired directly from the terminal by a third party contractor. The renewable component of the R80/B20 is the exact same product as the R100. The contractor assured SwRI that the fuels were drawn from a terminal that supplied to service stations from a list that was supplied by CRC. The contractor placed the two fuels in pre-labeled drums and then shipped them to SwRI. Once the two fuels were received at SwRI they were logged in to the Fuel Inventory System (FIS) and given identifier codes, as listed above, which were applied to the respective drums. Additionally, CRC requested that hydrocarbon analysis be conducted on the renewable fuels via ASTM D2425 and ASTM D8368, as well as analysis of bulk modulus. The bulk modulus data is given in Table A-17. The ASTM D2425 data is given in Table A-18. Since neither SwRI, nor any other contract laboratories, offered in-house D8368 analysis at the time of this program, the samples were sent to VUV Analytics, Inc (manufacturer of the instrument) for analysis. Note that VUV Analytics, Inc. stated that they are not certified for D8368. The results of the D8368 analysis are given in Table A-18.

SwRI then prepared a 200-gallon 50/50 by volume blend of the R100 renewable diesel (CDF-11267) and the High T90 ULSD (EM-11302) that was received earlier at SwRI from Gage. After blending, the same analyses performed on the R100 and R80/B20 fuels were also performed on this fuel blend. Once the analyses were approved by CRC, the blended fuel was transferred from a stainless-steel tote, used to prepare the blend on a weight basis, to four new 55-gallon epoxy-phenolic lined drums.

2.3 Emission Test Cell and Instrumentation

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 21. This test cell was a transient capable test cell meeting the requirements of 40 CFR Part 1065 for emission certification testing. 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 THC, CH_4, NMHC, CO, CO_2, and NO_X. Tailpipe particulate matter (PM) measurements were made via SwRI's proprietary secondary dilution system. In addition to the Dilute measurements, an FTIR was also used in the Raw exhaust at the tailpipe to monitor NO, NO_2, NH_3, N_2O, and SO_2, as well as CO_2 and other gases for quality assurance purposes.

Engine-out emissions were also monitored using Raw measurement techniques. A Horiba MEXA 7100DEGR raw emission bench was used for engine-out measurements of THC, CO, CO_2, NO_X, NO, and O_2, as well as intake manifold CO_2 measurement to allow for independent calculation of the EGR rate. Raw exhaust flow measurement was performed via intake air flow measurement using a laminar flow element (LFE) and the chemical balance calculations in 40 CFR Part 1065.650 and 1065.655.

An additional FTIR was also utilized at the outlet of the LO-SCR catalyst in the system to further monitor NO, NO_2, NH_3, N_2O, SO_2, and CO_2. This additional instrument allowed for a more detailed analysis of the impact of fuels on system performance.

To support combustion and hardware development, a high-speed data acquisition system was used to monitor cylinder pressure and fuel injector current on all 6 cylinders. This was crucial for the development and monitoring of systems such as cylinder deactivation, as well as for monitoring combustion stability and performance during calibration development. For this fuels program, the presence of the high-speed data acquisition system allowed monitoring of combustion stability so that it would be possible to detect issues arising from the use of any particular fuel. Later in the program, this instrumentation was leveraged for some steady-state testing to help provide greater insight into the results observed with some of the test fuels.

Most of the additional sensors and actuators used on the test engine 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 for the engine, and 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 on 40 CFR Parts 1065, 86, and 1036. 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 every test across all cycles. Even when maintained within the recommended 2% range, this still allowed for variation over time and among fuels. In order to enable meaningful comparison of CO_2 emission results over the course of the program, tailpipe CO_2 emission results were corrected to place them on the same carbon balance basis as the original engine baseline emission results. This allowed for direct comparison to previous Stage 3 results.

For the regeneration testing specifically, additional instrumentation was added at the engine-out location in the form of an AVL 483 MicroSoot Sensor (MSS). This instrument was used for real-time measurement of engine-out soot rate during repeat FTP testing. This information was used along with recorded aftertreatment system pressure drop data to assess the impact of selected fuels (B20 and R100) on soot accumulation rates on the DPF, as compared to a base diesel fuel.

2.4 Test Cycles, Test Procedures, and Preconditioning Procedures

2.4.1 Criteria Pollutant Testing

For the evaluation of direct fuel impacts on criteria pollutants, tests were run in triplicate using the sequence shown below in Table 9.

TABLE 9. CRITERIA POLLUTANT TESTING SEQUENCE

Emission Testing Day Sequence (1 shift)	
Current Day Fuel	Cold FTP
	Hot FTP
	Hot FTP
	Hot FTP
	LLC
	RMC-SET
Next Day Fuel	Fuel Change
	PV / Clean-out
	2 FTP Preps

The test process for a given test day sequence is outlined in more detail below (the outline assumes that the engine was already preconditioned for testing on the test fuel the day before).

- One cold-start FTP
- 20-min engine-off soak
- Three successive hot-start FTP (with a 20-min engine-off soak between tests)
- 20-min engine-off soak
- One LLC
- One RMC-SET test set (containing its own preconditioning cycle)

All testing and preconditioning was conducted in accordance with the procedures given in 40 CFR Part 1036 and 40 CFR Part 1065.

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

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

Preconditioning for the LLC involves running at least one hot-start FTP transient cycle. If the test sequence is run as described above, the final FTP hot-start test of the FTP 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 engine-off soak. However, in the event the sequence was interrupted, a preconditioning hot-start FTP transient cycle would be run, followed by a 20-minute engine-off soak and then the LLC test itself.

2.4.2 Regeneration Impact Testing

The objective for the regeneration impact testing was to make a relative assessment of passive soot oxidation and DPF soot accumulation behaviors in comparison to the baseline fuel. Work to project the regeneration frequency for the baseline case has been done previously for the Stage 3 program, in order to enable the calculation of active regeneration frequency, which is in turn used to calculate the IRAF (which in this case is an Upwards Adjustment Factor or UAF). The regeneration frequency is driven by the passive soot oxidation behavior of the zCSF in the system, and it varies by duty cycle.

On the RMC-SET, temperatures are high enough to enable high rates of passive soot oxidation on any fuel, and therefore fuel effects are unlikely to be seen. On the LLC, temperatures are too low to enable effective passive soot oxidation on any fuel, and therefore it would be possible to directly calculate regeneration frequency impact based only on engine-out PM measurements. Therefore, this evaluation was focused on the FTP cycle, which was most likely to be impacted by different fuels because it is closer to a balance point between soot loading and soot oxidation, although favoring slow accumulation of soot over time. As a result, fuel impacts could significantly impact regeneration frequency in a positive or negative fashion. In addition, the FTP cycle shows a small compliance margin for the baseline fuel, meaning that the results are most relevant to the analysis.

The test sequence for regeneration impact testing was as follows:

- A DPF regeneration was conducted on the baseline fuel (as this would not impact the results and would save fuel from the limited fuel supply available).
- The fuel was switched to the candidate test fuel in question, and the engine was run at moderate load enough to flush the previous fuel from the engine fuel system.
- Following the fuel system flush, the engine was shutdown.
- A preconditioning FTP was run, following by engine shutdown and a 20-minute soak.
- A sequence of up to 12 successive hot-start FTPs was run, with a shutdown and 20-minute engine-off soak between tests.
- At the end of the FTP sequence, the engine was shut down and soaked for 20 minutes, after which a single LLC was run

During the course of regeneration impact testing, the differential pressure across the zCSF was monitored. In addition, the AVL 483 Micro Soot Sensor (MSS) was used to monitor engine-out soot rate rates. Data from the candidate fuels was compared to the rate of soot emission and accumulation on the baseline fuel to project the impact on regeneration frequency.

If a change in projected regeneration frequency was observed for a given fuel, SwRI used that information to re-calculate the UAF for the FTP and/or the LLC. An example of the UAF calculation for the baseline fuel on the Stage 3 engine over the FTP cycle is given below in Figure 9. Note that in this figure EFL refers to the average emission level over a cycle without regeneration (the "normal" emission performance of the system), while EFH refers to the average emission level over a cycle with regeneration (including the impact of any subsequent cycles where emissions are recovering to a normal level).

Inputs	Cycles	Hours	$TPBSNO_X$, mg/hp-hr	Weighted NO_X mass	
Normal ftp	92	30.67	17	521	mg
Regen ftp	2	0.67	116	77	mg
Recovery ftp	1	0.33	50	17	mg
Total ftp	95	31.7		615	mg
				19	mg/hp-hr
	EFL	**17**	**mg/hp-hr**	2	*mg/hp-hr*
	EFH	**94**	**mg/hp-hr**		
			Upward Adjustment Factor		
Regeneration freq (F)	**0.031579**		**UAF**	**2.4**	mg/hp-hr

FIGURE 9. EXAMPLE OF UAF CALCULATION FOR THE FTP CYCLE ON THE STAGE 3 ENGINE WITH BASELINE ULSD FUEL

3.0 RESULTS AND DISCUSSION

This section of the report details the test results and provides analysis of the data. The first part of this section deals with the impact of the various test fuels on tailpipe emissions over the regulatory cycles. The second part describes the impact of selected test fuels on the soot loading behavior of the DPF.

3.1 Impact of Fuels on Criteria Pollutants over Regulatory Cycles

This part of the report is focused on the impact of the various test fuels on tailpipe emissions from the Stage 3 Low NO_X Engine. As discussed earlier, each of the 8 program fuels was tested in triplicate over the three regulatory cycles that will be used for model year 2027 and later heavy-duty diesel engines. These cycles include the transient FTP (which includes both cold-start and hot-start phases), the higher load RMC-SET, and the new Low Load Cycle (LLC). Comparison data is also given in the section for the 2D EPA Certification test fuel that was used during all prior testing and development on the Stage 3 engine. The result summary is focused primarily on NO_X and PM emissions, as these are the primary pollutants of concern for this test program. NMHC emissions for the Stage 3 engine are about 1/3^rd^ of the standards adopted by EPA and did not appear to be significantly influenced by fuels. CO emissions for the Stage 3 engine are at a level below 5% of the standards adopted by EPA, and although these levels were somewhat reduced for both biodiesel blends and the R100 fuel, all fuels were still well below the standard limits for CO.

3.1.1 Fuels Impact on NO_X Emissions

A summary of tailpipe NO_X emissions results for the various fuels tested is given in Figure 10. The levels show in the figure represent the average of 3 test runs, while the error bars are the standard deviation across those three runs. In the case of the 2D fuel, the data is an average across six test events, and the error bars represent the long-term standard deviation of the Stage 3 engine across multiple test events over the course of the prior 2 years.

The results are grouped together in the figure with the three program conventional diesel fuels, and the 2D EPA Certification fuel to the left. The biodiesel blends are shown grouped together, and it should be noted that the B20 and B50 blends used the Hi T90 diesel fuel as the base fuel for the blend. The B20R80 fuel uses the renewable diesel (R100) as the base fuel for the blend. Finally, the renewable fuels and renewable fuel blends are grouped together. Note that the R50 fuel also uses the Hi T90 diesel as the base fuel for that blend.

A summary of engine-out NO_X results is given in Figure 11 for the various program fuels and the 2D EPA certification fuel for comparison.

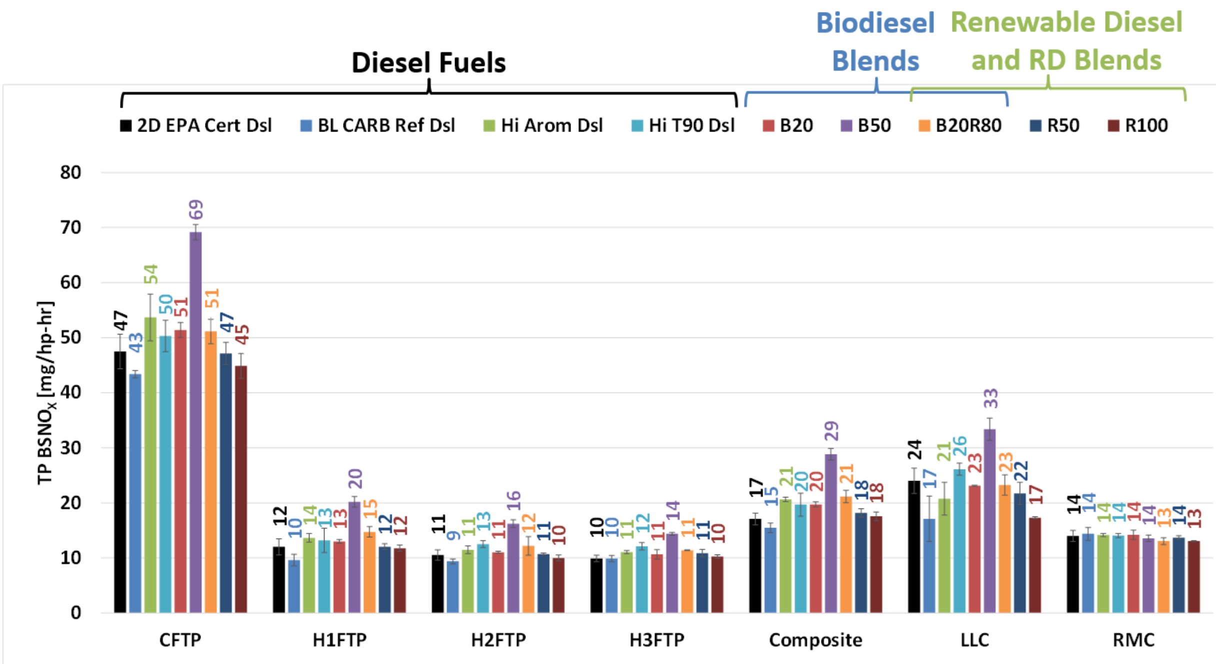

FIGURE 10. TAILPIPE NO_X EMISSIONS SUMMARY FOR VARIOUS TEST FUELS

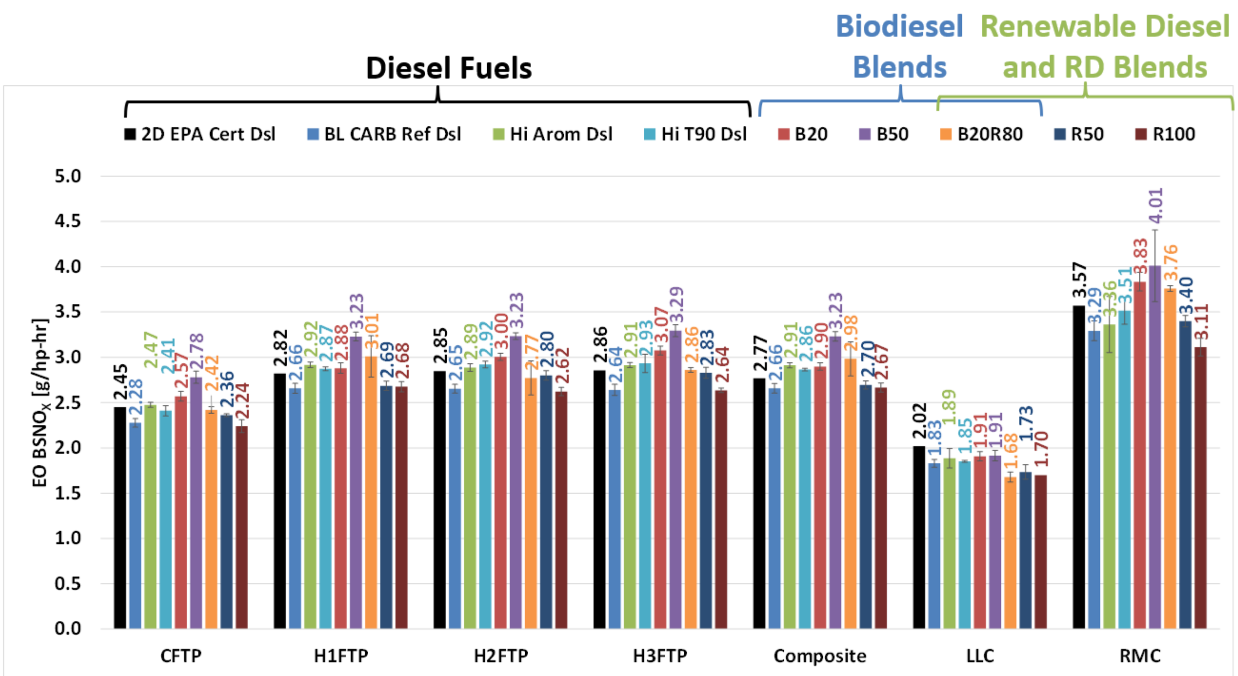

FIGURE 11. ENGINE-OUT NO_X EMISSIONS SUMMARY FOR VARIOUS TEST FUELS

The data is also summarized in terms of aftertreatment performance by looking at NO_X conversion efficiency in Figure 12. NO_X conversion efficiency is calculated as the difference between engine-out and tailpipe NO_X levels, divided by the engine-out NO_X level.

A number of trends can be observed when examining these NO_X data sets regarding the impact of the various test fuels on NO_X emissions. It was noted that the impact of fuels on both engine-out and tailpipe NOx varied considerably by duty cycle, though not always in the same manner. For the high load RMC-SET cycle, tailpipe NOx emissions were insensitive to any fuel changes, with all of the results being within the range of +/- 1 mg/hp-hr which is in the range of repeatability of the Stage 3 test engine. On the other hand, engine-out NOx emissions varied considerably with fuel type, with increased NOx observed for the biodiesel blends being slightly above the range observed for the conventional diesel fuels, and somewhat decreased for the renewable diesel fuels. The largest engine-out NOx increase was seen for the B50 fuel, while the largest decrease was observed on the R100 fuel. It should be noted that on the RMC-SET, aftertreatment temperatures are consistently well above 200°C and are usually greater than 300°C. At those high temperatures, the AT system has sufficient conversion efficiency to handle the observed engine-out NOx variation without seeing an impact on tailpipe NOx emissions.

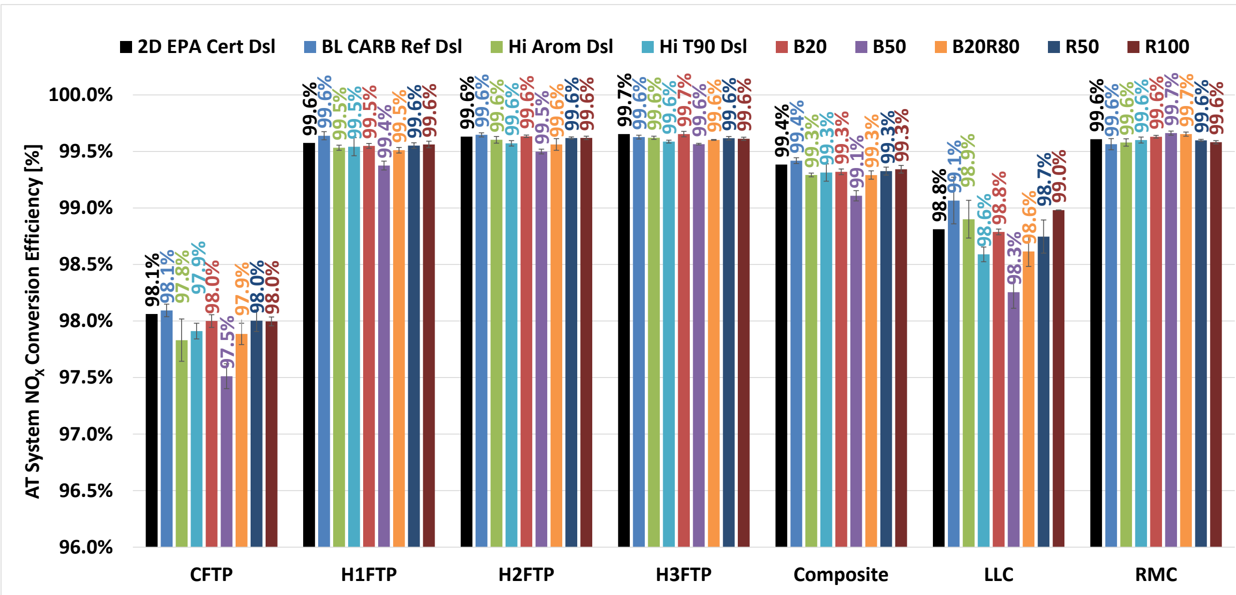

FIGURE 12. AT SYSTEAM NOx CONVERSION EFFICIENCY FOR VARIOUS TEST FUELS

For the FTP, engine-out NOx emissions were also seen to vary by fuel, with the trend being similar to that observed for the RMC-SET, although the changes were generally smaller in magnitude. However, unlike the RMC-SET, variations in tailpipe NOx were observed as well, due to the lower cycle exhaust temperatures on the FTP. On the conventional diesel fuels, the cold-start NOx varied over a range from 43 mg/hp-hr to 54 mg/hp-hr. All of the biodiesel blends and renewable fuels were within that same range, with the exception of the B50 fuel which showed a substantial increase in cold-start NOx to nearly 70 mg/hp-hr.

Similar trending was observed on the hot-start FTP with the magnitude of the variations being smaller. As a result, for the composite FTP, the conventional diesel fuels were seen to vary over a range of 15 to 21 mg/hp-hr, compared to 17 mg/hp-hr for the EPA 2D certification fuel, with most of the other fuels, including the B20 blends and the renewable diesel fuels and blends, also falling within the same range. It was observed that the B20, which was blended with Hi T90 diesel fuel, had engine out and tailpipe emissions identical to the Hi T90 diesel fuel, while the B20 made with R100 as the balance fuel did result in an upwards shift in NOx as compared to the renewable diesel balance fuel alone. It was noted that the R100 fuel was always near the bottom of the range, as was the CARB Reference diesel fuel. Again the B50 blend was an exception with that fuel showing an FTP NO_X increase of 12 mg/hp-hr. One behavior that was also noted for the hot-start FTP as that the fuel impacts became smaller with each successive hot-start in the test sequence, with third final hot-start showing much smaller fuel trends than the first hot-start. This indicates some capacity for the system to absorb the changes over time, even for the B50 fuel.

For the LLC, on the other hand, engine-out NO_X emissions were much less sensitive to fuel, although it was observed that the renewable diesel fuels did generally improve engine-out NO_X emissions over the LLC compared to the other fuels. The tailpipe NO_X trend over the LLC was similar to that observed on the FTP, but the variations were somewhat larger. The conventional diesel fuels varied over a range of 17 to 26 mg/hp-hr, as compared to 24 mg/hp-hr on the EPA 2D certification fuel, with the other fuels apart from B20 being in that same range. As before, R100 and CARB reference diesel had the lowest tailpipe NO_X levels. Similar, B50 demonstrated the largest tailpipe NO_X increase of 11 mg/hp-hr.

The larger increases in tailpipe NO_X observed for the B50 fuel on the FTP and the LLC were due to more than just the change in engine-out NO_X. NO_X conversion efficiency was also noted to drop on those two cycles with the B50 fuel. The reason for this drop in AT system efficiency can be seen in Figure 13 for the FTP, and Figure 14 for the LLC, respectively.

In both figures it can be seen that the B50 fuel generally results in the temperatures of both the upstream LO-SCR and the downstream underfloor SCR catalysts being about 10-15°C lower over both cycles, as compared to the baseline diesel fuel. In areas where this temperature drop coincides with operation where exhaust temperatures with the baseline fuel are at or below 200°C, it can be seen that this temperature drop results in a loss of NO_X conversion and an increase in tailpipe NO_X emissions at that point. This can be seen in how these regions coincide with a sharper increase in cumulative tailpipe NO_X in the figures. This is due to the fact that for the copper zeolite SCR catalysts used on this engine, the area around 200°C and below corresponds to a temperature range where SCR catalyst performance is on a relatively steep slope in terms of the relationship between NO_X performance and temperature.

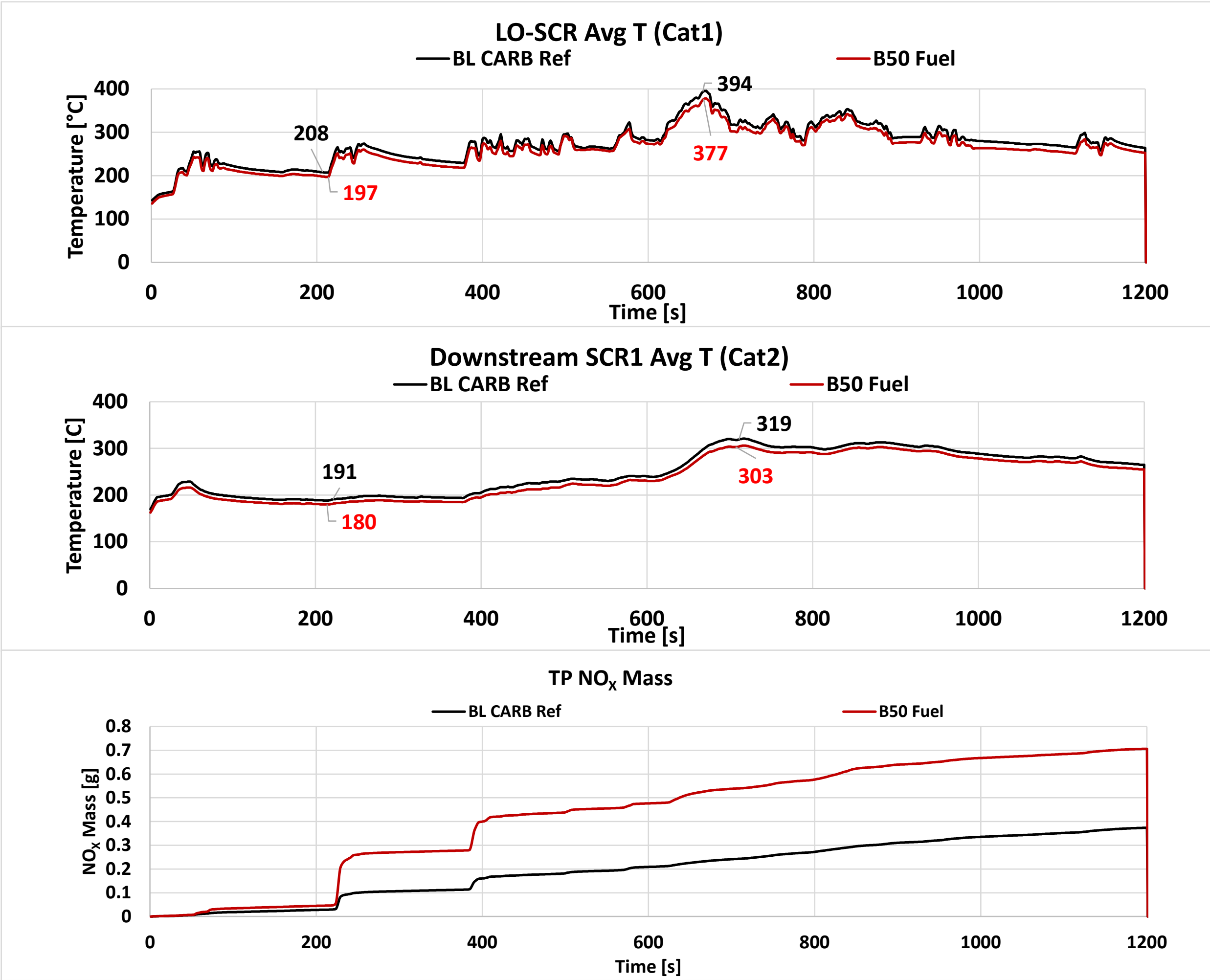

FIGURE 13. HOT-START FTP TEMPERATURE AND NO$_X$ DATA – B50 VERSUS BASELINE DIESEL FUEL

This change in temperature with B50 is due to the significant reduction in energy content that is metered into the cylinder under full load acceleration conditions. Figure 15 shows a comparison of full-load torque curves for the Baseline fuel and for B50 and R100 fuels. Note that with the B50 fuel a loss of 4 to 5% is observed over much of the torque curve, especially in the area near peak torque. This is due to the presence of 5% oxygen in the fuel which does not contribute to combustion energy. The impact of this on a transient acceleration is illustrated in the example shown in Figure 16. This example is from one of the lower temperature portions of the hot-start FTP. As can be seen, during the period from 217 thru 222 seconds when the pedal command is at 100%, the engine running B50 cannot produce as much torque as the engine running the BL fuel, while at part loads the test cell can make up for the loss of torque with added pedal command. The result of this is that lower exhaust temperatures are generated during each of these acceleration events, which results in a cumulative loss of temperature across the cycle.

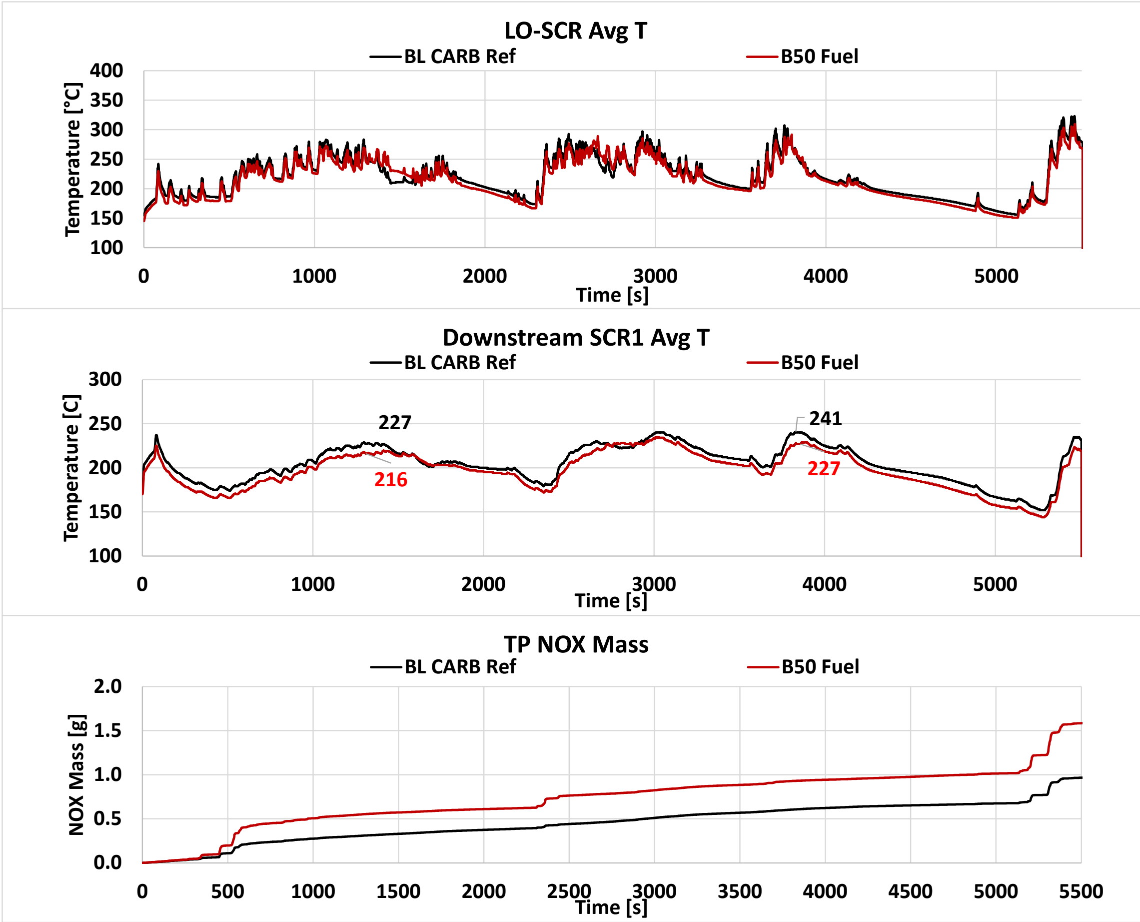

FIGURE 14. LLC TEMPERATURE AND TAILPIPE NO_X DATA – B50 VERSUS BASELINE DIESEL FUEL

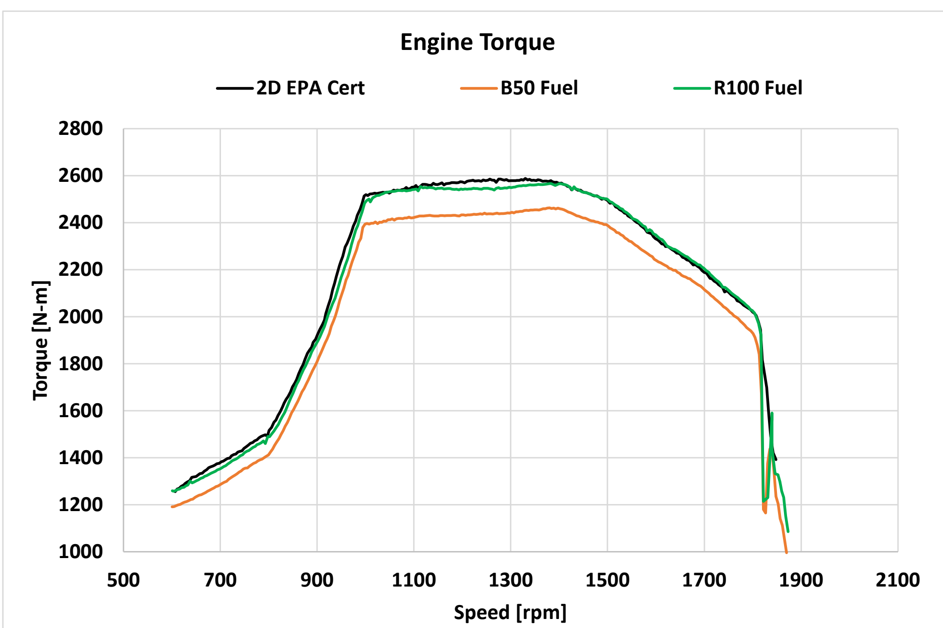

FIGURE 15. COMPARISON OF FULL-LOAD TORQUE CURVES FOR SELECTED FUELS

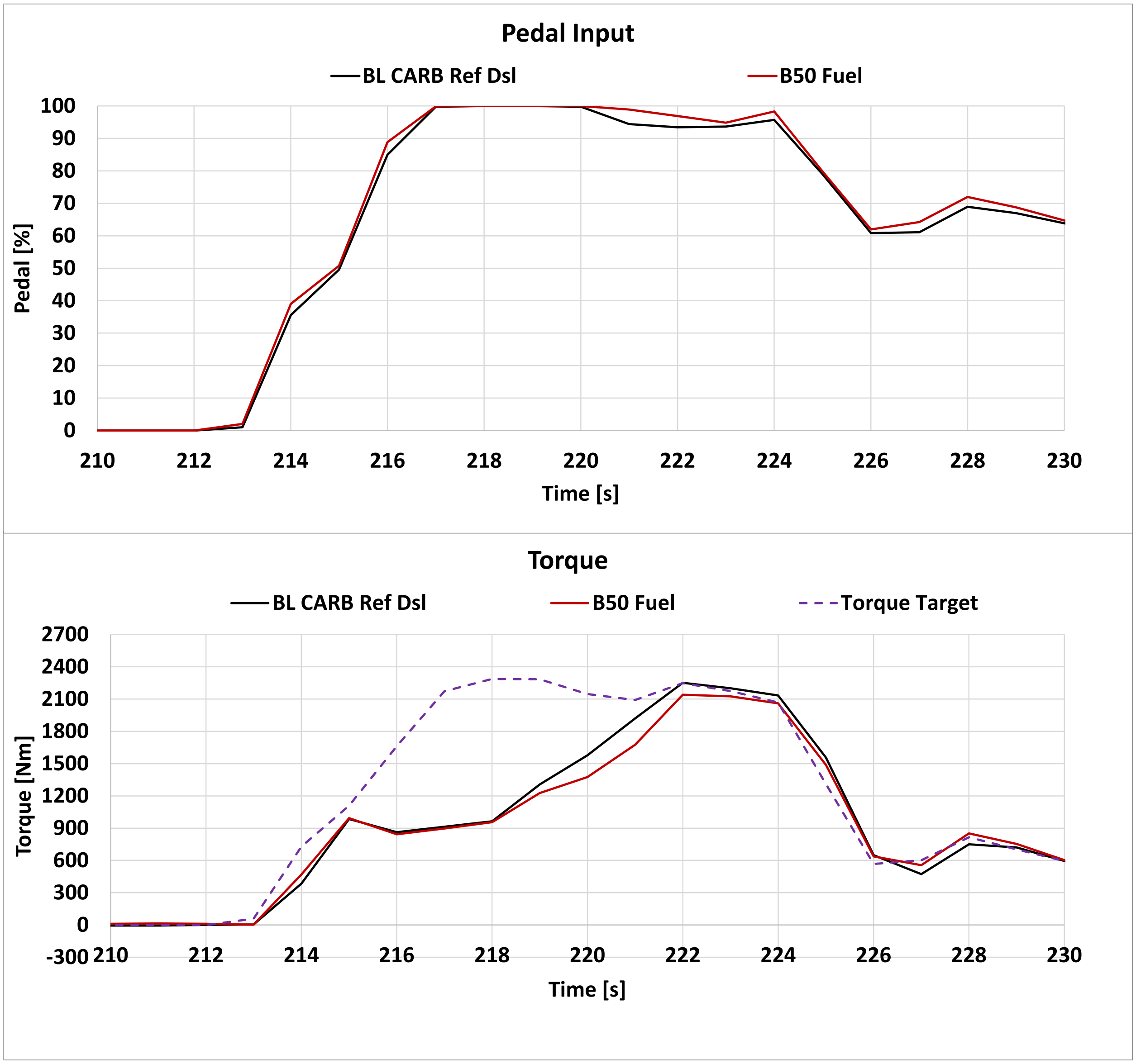

FIGURE 16. TRANSIENT ACCELERATION EXAMPLE COMPARING B50 WITH BASELINE DIESEL FUEL

Given the results above, the overall impact of fuels on the Stage 3 engine tailpipe NO_X was on the order of -2 to +4 mg/hp-hr on the FTP and -6 to +2 mg/hp-hr on the LLC, with the exception of B50 where the impacts were closer to +11 to +12 mg/hp-hr. For the RMC-SET cycle, fuels did not appear to impact tailpipe NO_X. It was generally noted that fuels with higher aromatic content tended to have higher tailpipe NO_X emissions. It should be noted that these values represent the outer limits of the range of variation described by the fuels in this test program, and it would be reasonable to assume that the range of actual fuel impacts would fall within these limits with some kind of random distribution, though the shape of that distribution is not discernible from this program.

However, it should be noted that these fuels would not be seen during this kind of certification testing, wherein diesel fuels meeting either EPA (2D) or CARB (BL) specifications would be used. Therefore, to understand the real impact of fuels it is important to try to place these results in context regarding the in-use emission standards and testing requirements that will be in place for MY 2027 and beyond.

Beginning in the MY 2010 timeframe, heavy-duty manufacturers have been responsible for conducting in-use testing via the use of Portable Emission Measurement Systems (PEMS) placed on vehicles during actual customer operation. Currently, these measurements are evaluated against Not-to-Exceed (NTE) standards, which generally apply only to operating events above 30% torque or power. Beginning with MY 2027, EPA will move to a new methodology for in-use compliance, with PEMS measurements assessed using a 2-bin Moving Average Window (2B-MAW) metric, wherein nearly all operation is included regardless of duty cycle. This methodology is outlined in 40 CFR 1065.530, and involves a 5-minute data window moved through the data set at 1-second increments. Emissions in these windows are sorted into bins depending on whether the normalized CO_2 emissions for a given window are above or below 6% of the maximum CO_2 rate for the engine. The accumulated emissions in each bin are then compared to the in-use standards given below in Table 10. It should be noted that for Bin 2 there is also an additional in-use NO_X compliance margin of 15 mg/hp-hr applied to for heavy-heavy duty (HHD) and medium heavy-duty (MHD) diesel engines that have been operated in commerce, making the final in-use standard 73 mg/hp-hr. There is also an incremental PEMS measurement allowance of 5 mg/hp-hr, but that is not considered in this analysis because all of the measurements involved were taken with laboratory instruments for which this PEMS allowance would not apply.

TABLE 10. EPA IN-USE EMISSIONS STANDARDS FOR MY 2027 AND BEYOND

Off-Cycle Bin	NO_X	Temperature adjustment [a]	HC mg/hp·hr	PM mg/hp·hr	CO g/hp·hr
Bin 1	10.0 g/hr	$(25.0 - \bar{T}_{amb}) \cdot 0.25$	—	—	—
Bin 2	58 mg/hp·hr	$(25.0 - \bar{T}_{amb}) \cdot 2.2$	120	7.5	9

In previous work [1], additional measurements on the Stage 3 engine have been made in a variety of field duty cycles representing widely varying applications with cycles that ranged from 6 to 9 hours in length. These measurements were made to assess the capability of the Stage 3 engine in the context of the new 2B-MAW in-use compliance standards. A comparison between these measurements and the regulatory cycle results can be used to help provide context for the fuel-related variations observed in this test program. In addition, manufacturers are responsible for in-use compliance out the 650,000 miles, and this can also be assessed using previous program data.

Table 11 shows a summary of regulatory and field cycle emissions on EPA 2D Certification grade diesel fuel. The results in bold are shown for the Development Aged parts that are used during this fuels program, as well as for parts that were aged to 650,000 mile equivalent. These numbers shown the relationship between the regulatory cycle results and the field cycle results for both aging points. This data can be used to assess the impact of the fuels results by scaling them from the Development Aged regulatory cycle results which compare directly to the fuels testing data from this program which are done using the same parts and cycles.

TABLE 11. REGULATORY AND FIELD CYCLE EMISSIONS FOR THE STAGE 3 ENGINE AT VARIOUS AGING POINTS

Cycle	**Dev Aged 435k**	DAAAC Aged 435k	DAAAC Aged 800k	**DAAAC Aged 650k**	**EPA**
	Cert Cycle TP NOX, mg/hp-hr				
FTP	**16**	20	37	**29**	**35**
RMC	**14**	17	29	**25**	**35**
LLC	**24**	29	32	**32**	**50**
	Field Cycle Bin 2 TP NOX, mg/hp-hr				
SNTE	**26**	32	47	**41**	**58 / 73**
ACES 5m	**18**	19	34	**28**	
Drayage	**20**	19	28	**24**	
EU-ISC	**17**	30	32	**31**	
Grocery	**21**	23	32	**28**	

Using the temperature data from both the field cycles and the regulatory cycles, it is possible to weight how the Bin 2 results for each field cycle appear to respond to changes in the three regulatory cycle emission levels. The resulting weight factors for each field cycle are shown in Table 12.

TABLE 12. WEIGHT FACTORS FOR INFLUENCE OF REGULATORY CYCLE CHANGES ON FIELD CYCLE BIN 2 RESULTS

Cycle	FTP	RMC	LLC
SNTE	50%	38%	13%
ACES 5m	30%	57%	13%
Drayage	11%	22%	67%
EU-ISC	33%	47%	20%
Grocery	27%	18%	55%

Using the data in Table 11 and the weight factors in Table 12, we can apply the loss of NO_X conversion efficiency due to aging observed in the prior programs to the fuel test results in this program. This results in a projection of the impact of fuel changes on the Bin 2 emissions of the Stage 3 engine at 650,000 miles for the various field cycles. It should be noted that this approach ignores any possible long-term influence of the given fuel on AT system durability. The resulting projected Bin 2 emissions for each fuel are shown in Figure 17, while the change in Bin 2 emissions compared to 2D fuel is shown in Figure 18.

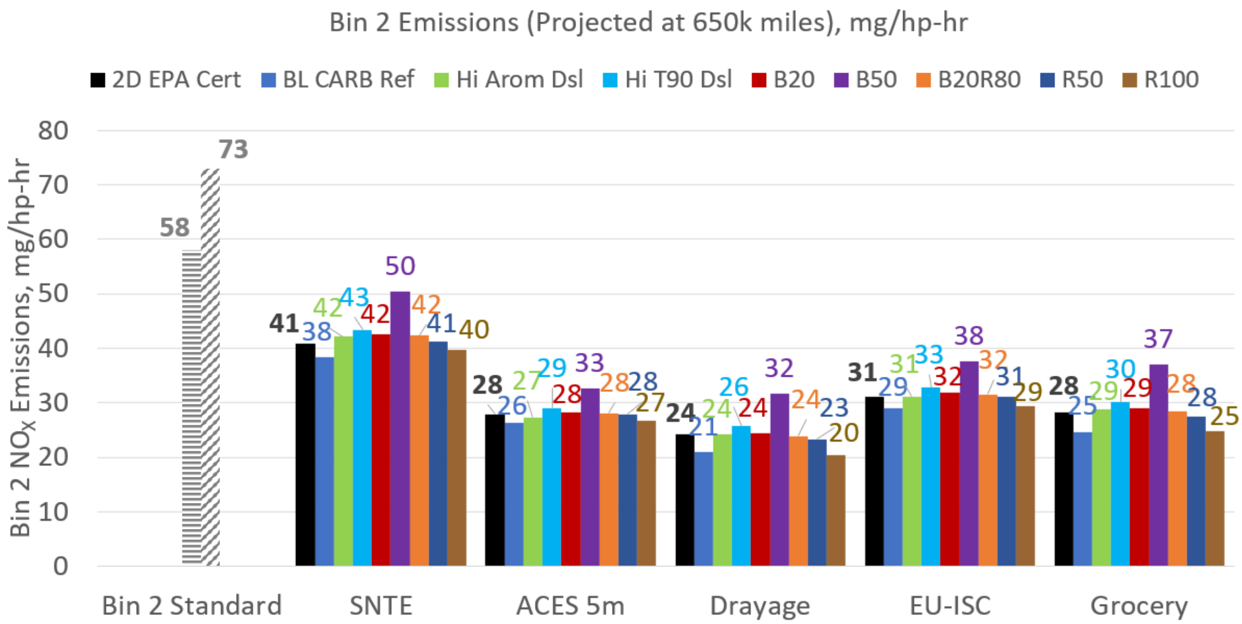

FIGURE 17. PROJECTED BIN 2 NO_X EMISSIONS FOR VARIOUS FIELD CYCLES ON DIFFERENT FUELS COMPARED TO MEASURED DATA ON 2D FUEL

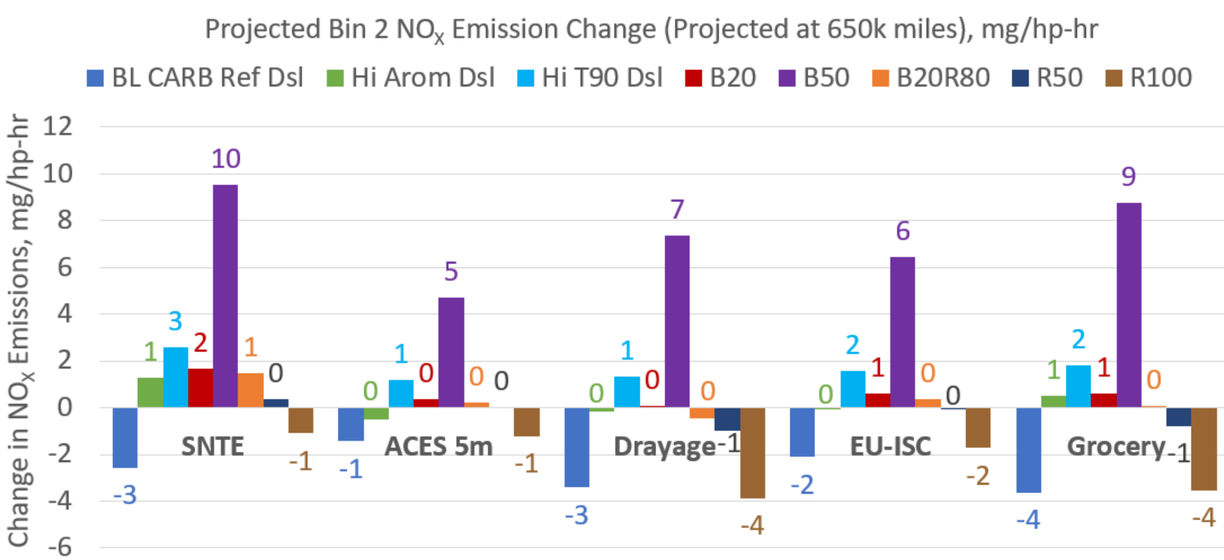

FIGURE 18. RELATIVE IMPACT OF DIFFERENT FUELS ON BIN 2 NO_X EMISSIONS ON VARIOUS FIELD CYCLES

The results show emission impacts on the various field cycles ranging from -4 to +3 mg/hp-hr for the various program conventional diesel fuels, while the renewable diesel fuels and blends are generally NO_X neutral or show an improvement in the case of R100 on lower load field cycles. For the worst case conventional diesel fuels (at the higher aromatic levels), this change in emissions is on the order of +5% of the off-cycle lab standard of 58 mg/hp-hr and +4% of the in-use standard of 73 mg/hp-hr. The B50 blend results indicate a significant increase in tailpipe NO_X of between 5 and 10 mg/hp-hr, depending on the cycle, which is on the order of 9 to 17% of the off-cycle lab standard and 7 to 14% of the in-use standard.

It should be noted that these values represent the full range of potential fuel impacts for the fuels sampled in this program, and it would be reasonable to assume that the range of actual fuel impacts in-use would fall within these limits with some kind of random distribution, though the shape of that distribution is not clear from these results.

3.1.2 Fuels Impact on PM Emissions

A summary of tailpipe PM emissions is given in Figure 19. It should be noted that PM is well controlled by the DPF in the system over all conditions, and therefore tailpipe PM levels are well below the 2027 standard of 5 mg/hp-hr (though the LLC is somewhat closer). There is no trend apparent across the different fuels the emerges above the variability observed for the baseline fuel.

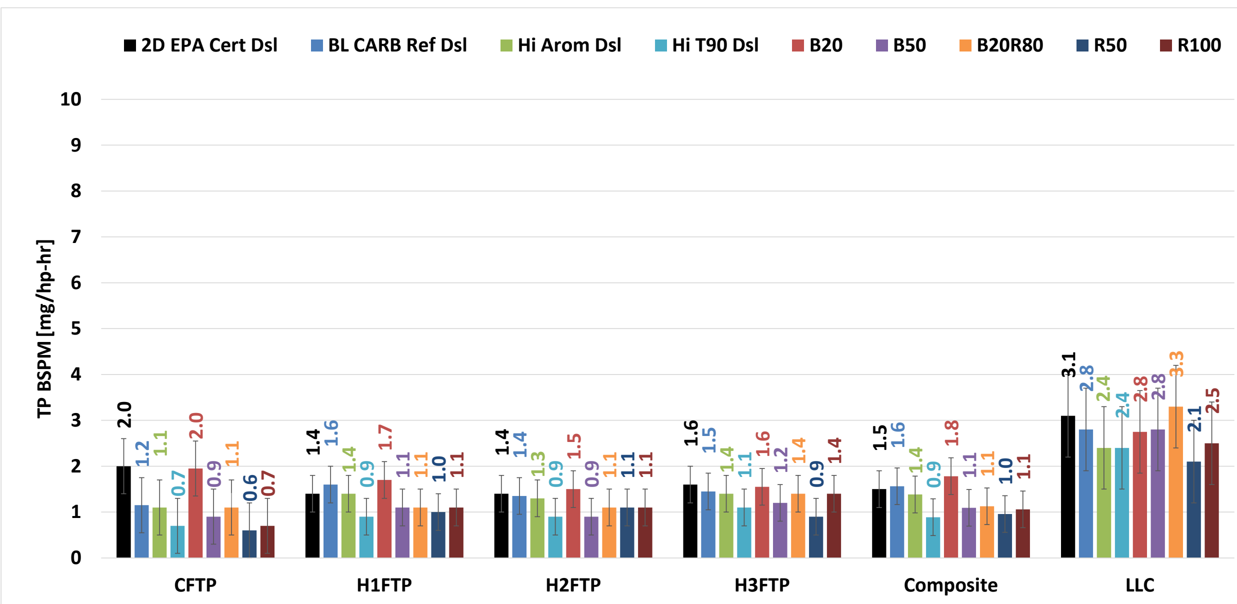

FIGURE 19. TAILPIPE PM EMISSIONS FOR VARIOUS FUELS

It should be noted that the RMC-SET cycle is not shown in this summary of PM emissions. Normally, RMC-SET PM emissions are observed at an average level of 0.0007 g/hp-hr +/- 0.0003 g/hp-hr. However, in some of the earlier tests, it was seen the PM levels on the RMC-SET were observed to be at a level closer to 0.003 g/hp-hr with a high level of variability. This behavior was note observed on the other test cycles, but only on the RMC-SET. After diagnostic runs, and the analysis of several filters for sulfates, it was determined that this was likely due to the release of stored sulfur during the highest temperatures of the RMC-SET. It was noted that by this point the DPF was well past the normal high temperature regeneration interval, and that this might be contributing to the release of excess sulfur. A high temperature regeneration was performed, which has to be done off-line on this test platform, after which the RMC-SET PM emissions returned to normal levels. A summary of PM levels of the baseline fuel before and after this event is given in Table 13. Note that the only cycle which showed a significant change was the RMC-SET, indicating that only RMC-SET PM results were impacted. Therefore they are not included in the summary in Figure 19. However, this does not change the conclusion that tailpipe PM was not affected by the various test fuels to any observable degree.

TABLE 13. PM EMISSIONS BEFORE AND AFTER HIGH TEMPERATURE REGENERATION

BL CARB Ref Fuel PM	PM, mg/hp-hr		
	FTP	LLC	RMC
Before HT Regeneration	1.5 +/- 0.6	2.6 +/- 0.8	3.5 +/- 1.0
After HT Regeneration	1.2 +/- 0.6	2.1 +/- 0.8	0.5 +/- 0.3

3.1.3 Fuels Impact on Measured Tailpipe CO_2 Emissions

A summary of measured tailpipe CO_2 emissions for all fuels on the various test cycles is given in Figure 20. The values are strictly the measured values at the tailpipe, and they have not been adjusted in any way to account for upstream related emissions. In addition, the values reported below have not been adjusted to reflect different energy content in the fuel. However, it should be noted that, as discussed earlier, all cycles were run using the target duty cycle for the Baseline diesel fuel, so that fuels with lower energy content were essentially driven harder by the test cell (e.g. more aggressive pedal usage) to reach the same cycle work targets (to the degree possible).

The conventional diesel fuels demonstrated values on the FTP ranging from 514 to 533 g/hp-hr, a range of 3 percent variation due to fuels. The B20 blend fell within this range, while the B50 blend was just above that. On the other hand, the R100 and renewable diesel blends demonstrated improved CO_2 emissions in many cases. The R50 does show a significant reduction of 3% in CO_2 compared to the Hi T90 diesel which makes of the balance of that blend. Similar trends are observed on the LLC and even the RMC cycle, although the range of variation on the RMC-SET is closer to 2 percent for the diesel fuels. However, even on the RMC, the renewable diesel and blends with significant renewable diesel content demonstrated significant tailpipe CO_2 improvements, with the R100 improving CO_2 by nearly 5%. This CO_2 improvement with the renewable diesel fuels appears to be a combination of the high H/C ratio of the fuel (lower carbon content), higher energy density, and an improvement in combustion phasing due to very high cetane (> 75 cetane number for the R100 fuel).

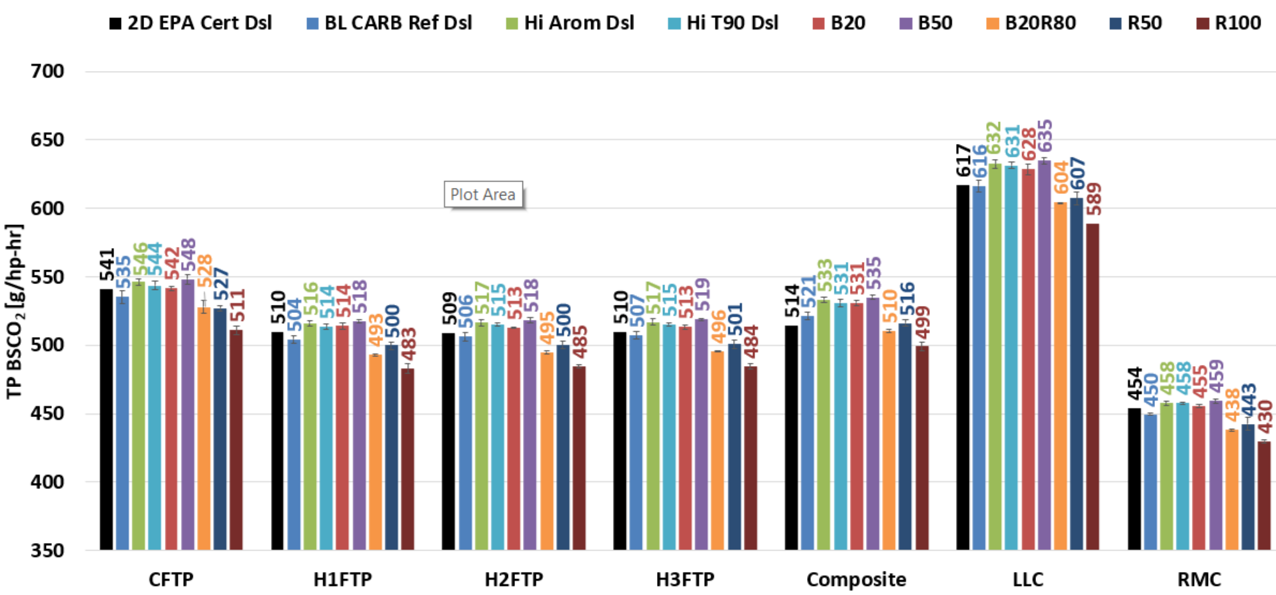

FIGURE 20. TAILPIPE CO_2 EMISSIONS FOR VARIOUS TEST FUELS ON REGULATORY DUTY CYCLES

Steady-state measurements with high-speed data acquisition of cylinder pressure and other parameters were taken at a number of conditions with the R100 fuel in comparison the Baseline fuel. Data with B50 was also taken as an example of the lowest energy content fuel. An example of this data is given in Figure 21. As noted earlier, the B50 fuel was not able to reach the same full load performance as the other fuels, being about 5% low on power and 2% low on cycle work. The R100 shows an advance in CA50 and higher P_{max} indicating an advance in combustion phasing, likely as a result of the very high cetane number. This results in improvement of 2-2.5% in BSFC is noted in the figure below.

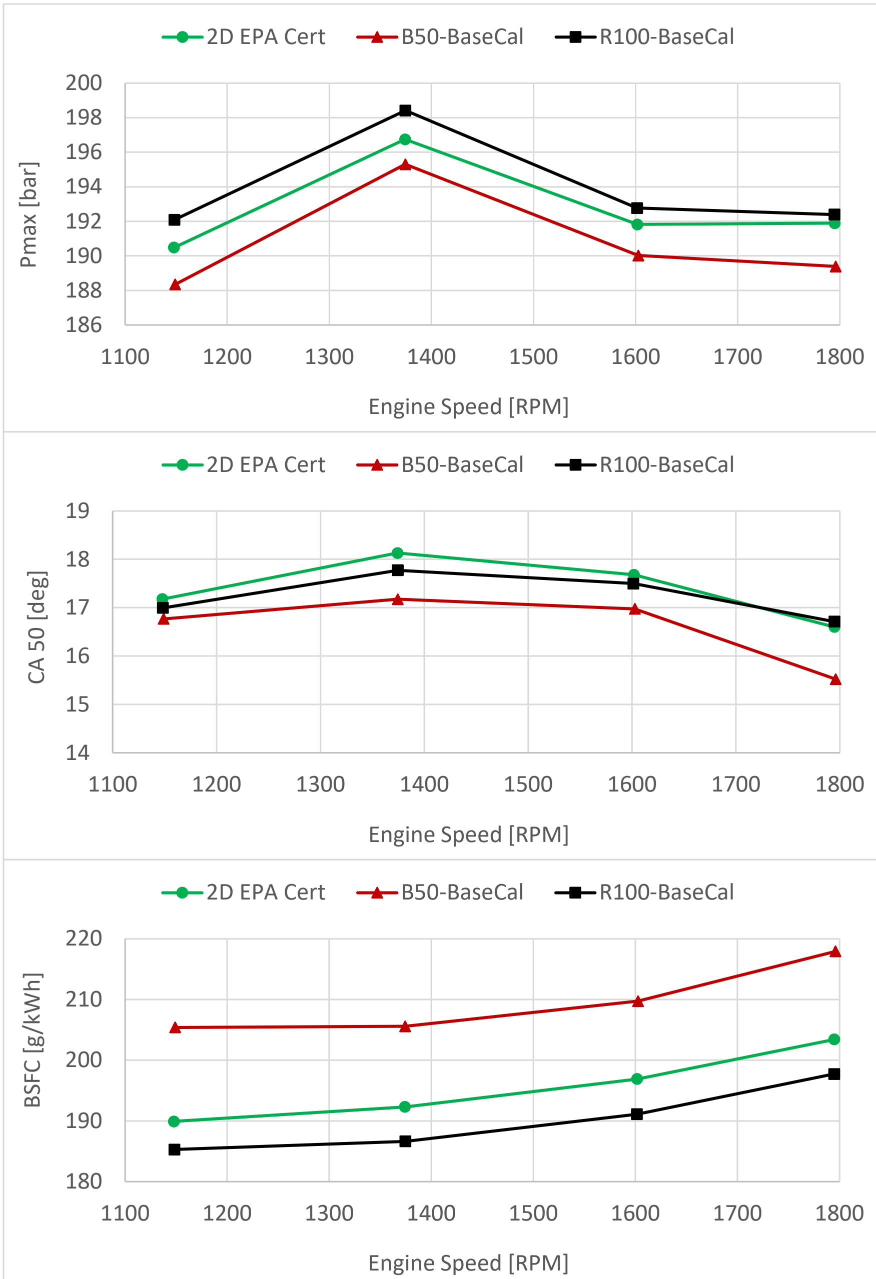

FIGURE 21. COMBUSTION DATA AT FULL LOAD FOR R100 AND B50 COMPARED TO EPA 2D FUEL

This improvement in combustion behavior for the R100,combined with 2% less carbon by weight, results in a 4-5% reduction in overall CO_2 emissions.

3.2 Impact of Fuels on Soot Loading and Regeneration Behavior

The soot loading and regeneration impact testing was conducted on a subset of the test fuels for the program. These include the CARB Reference baseline (BL) fuel, the B20 blend, and the R100 fuel.

The BL fuel testing was run first to establish the soot loading the DPF differential pressure characteristic baseline for the Stage 3 engine. Although this testing had been run previously during the earlier Stage 3 work, there were some calibration changes on the engine prior to the current run. Therefore, the BL testing was run to validate the baseline characteristic and also to characterize behavior on the BL fuel, which was different from the EPA 2D fuel that was used prior to this program. To ensure that the characteristic was fully established it was decided to run several extra hot-start FTP runs to make sure the baseline was well established. Following the DPF regeneration, a sequence of 15 repeat hot-start FTP tests were run on the BL fuel, with 20-minute engine-off soak between FTP tests as normal.

For the other two test fuels, repeat FTP tests were run until a clear characteristic was established that could be compared to the BL fuel. A regeneration was performed before the start of testing in each fuel. This was important in the case of the R100 fuel because there was a limited amount of that fuel remaining. However, in both the B20 and R100 cases, a clear trend was established after 10 FTPs and 8 FTPs, respectively, so that additional runs were not needed.

In all cases the AVL 483 Microsoot Sensor (MSS), was used to monitor engine-out soot rate in real-time during these hot-start tests. There was some initial variation in engine-out soot and conditions on the first hot-start FTP in each test sequence, but by the second hot FTP test, consistent operation was achieved and the relative rate of soot emissions between fuels could be compared.

A comparison of engine-out soot rate and accumulated soot mass emitted by the engine is shown in Figure 22. These data show is second hot-start FTP test in each sequence. Note that in all cases there are two distinct regions of soot emission from the engine. In the first 500 seconds of the cycle, the engine is in thermal management modes, and the engine-out soot rate is higher. At this point, DPF temperatures are generally below 300°C and no passive soot oxidation is occurring. For the remainder of the cycle, the engine is generally in the fuel economy mode, and the engine-out soot rate is lower. DPF temperatures are generally over 300°C between 600 and 900 seconds in the cycle, and therefore passive soot oxidation is occurring at this point. Generally, there is not quite enough passive soot oxidation to overcome the early soot loading on the FTP, so there is some residual soot loading left after each cycle. This results in an increasing DPF dP trend, show in Figure 23. While the general trend of increasing soot loading and DPF dP was present for all three fuels, there were significant differences observed for the different fuels.

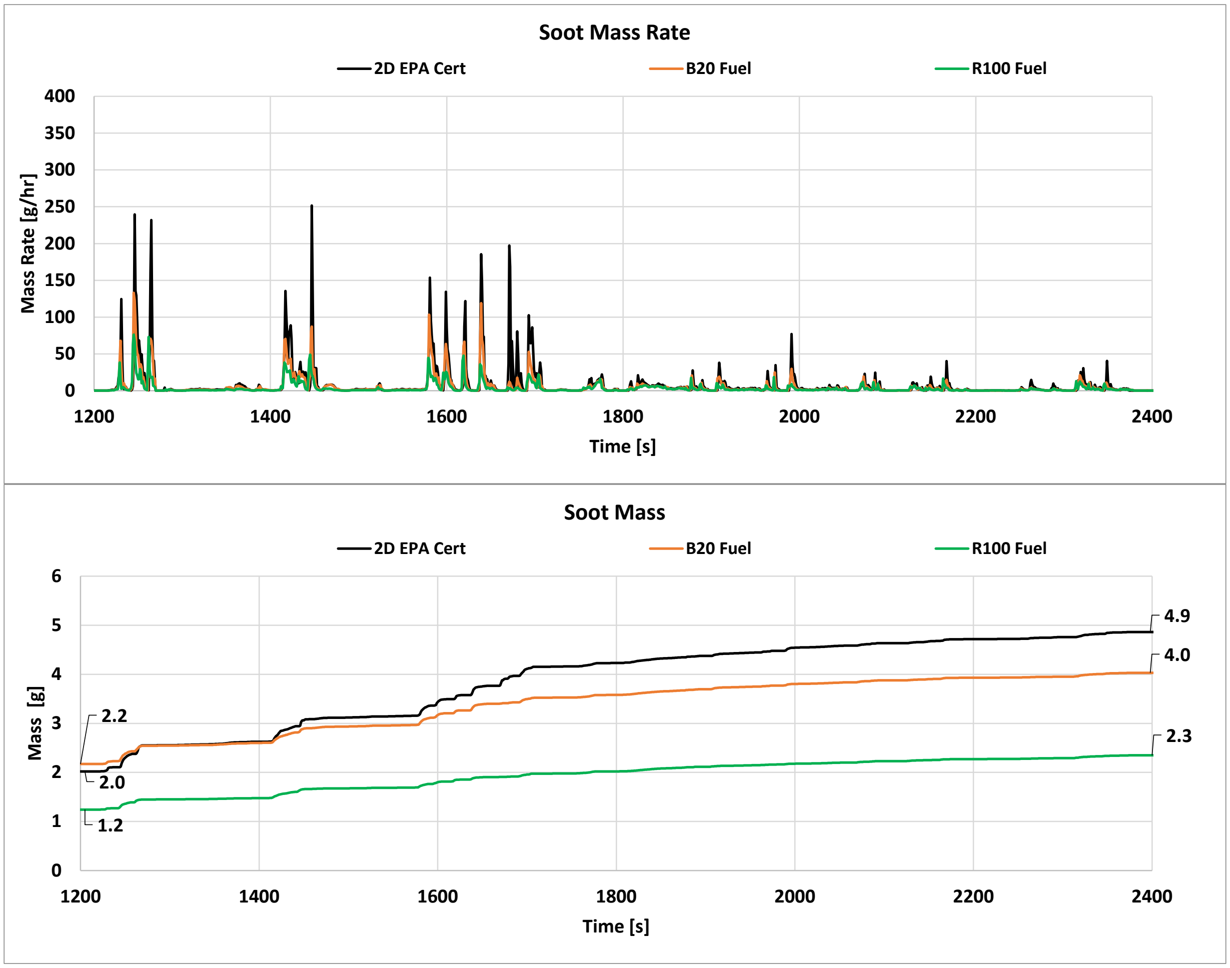

FIGURE 22. COMPARISON OF ENGINE-OUT SOOT RATE AND ACCUMULATED SOOT MASS ACROSS VARIOUS FUELS

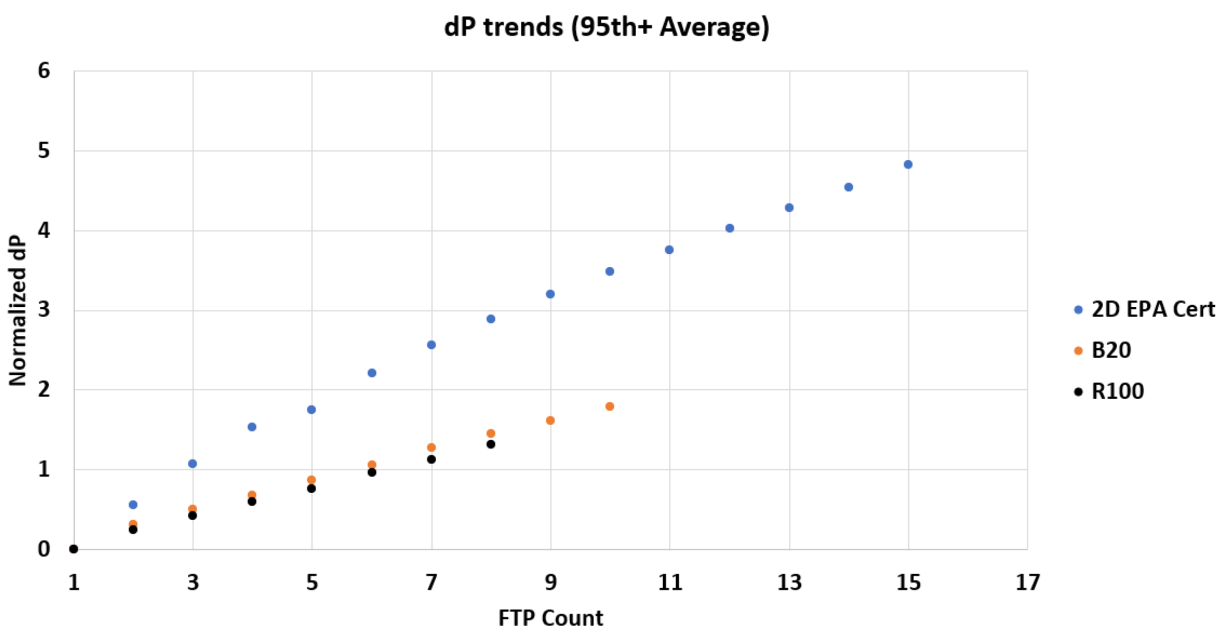

FIGURE 23. DPF DIFFERENTIAL PRESSURE (DP) OVER REPEAT HOT-START FTP TESTS FOR VARIOUS FUELS

As shown in Figure 22, the soot engine-out soot rate for the B20 was significantly lower than for the BL fuel, with many of the transient soot spikes during accelerations appearing to be about half as large for the B20 as compared to the BL fuel. Overall, 40% less soot mass was emitted on the B20 fuel as compared to the BL fuel. This difference is due primarily to the presence of roughly 2% oxygen in the fuel, with the localized oxygen helping to oxidize soot in the fuel rich portions of spray plume during the early stages of combustion. For the R100 fuel, the affect was even larger with a 67% reduction in accumulated soot mass emitted over the FTP cycle. In the case of the R100, this reduction is likely due to the fact that the fuel itself is almost entirely paraffinic in composition, with almost no heavy aromatic and PAH molecules that are generally held to be precursors for soot formation. This reduced soot emission rate would be expected to have a significant impact on the rate of soot loading on the DPF.

As shown in Figure 23, this is in fact the case, with both the B20 and the R100 fuel showing a rate of dP rise on the DPF that is half of what is observed for the BL fuel. In this case of the R100 fuel, this is likely due entirely to the reduced engine-out soot rate with that fuel. However, in the case of the B20 the dP behavior was just as favorable as the R100, even though the engine-out soot rate was still nearly twice that of the R100 (though still much lower than the BL diesel). This is likely indicating that more passive soot oxidation is occurring during the higher temperature portion of the cycle, which helps to balance out the higher engine-out soot rate compared to R100. Reactivity of soot has been studied previously for both diesel and biodiesel fuels[6]. It is understood that biodiesel and biodiesel blends tend to produce soot with a more open structure, as a consequence of the local oxygen content in the fuel. This more open structure allows more access for NO_2 during passive soot oxidation, and therefore leads to a soot that is more reactive under passive regeneration conditions. That phenomenon is likely why the B20 is able the match the lower rate of dP rise for the R100, even at a higher engine-out soot rate.

Figure 24 shows an updated set of infrequent regeneration calculations if the FTP rate of soot accumulation is half the original baseline. This would reduce the UAF from 2 mg/hp-hr to 1 mg/hp-hr. In addition to this impact, less frequent regenerations would likely lead to less degradation on the downstream SCR due to high temperature exposure during regenerations, which could result in an improvement in long-term durability, although this would have to be verified via experiment.

Inputs	Cycles	Hours	TPBSNO$_X$, mg/hp-hr	Weighted NO$_X$ mass	
Normal ftp	180	60.00	17	1020	mg
Regen ftp	2	0.67	116	77	mg
Recovery ftp	1	0.33	50	17	mg
Total ftp	183	61.0		1114	mg
				18	mg/hp-hr
	EFL	17	**mg/hp-hr**	1	*mg/hp-hr*
	EFH	94	**mg/hp-hr**		
			Upward Adjustment Factor		
Regeneration freq (F)	**0.016393**		**UAF**	**1.3**	mg/hp-hr

FIGURE 24. REVISED UAF CALCULATIONS USING SOOT ACCUMULATION RATE AT HALF THE BASELINE

3.3 Sulfate Analyses on Selected PM Filters

As an additional task in the program, batches of PM filters were analyzed to determine the portion of tailpipe PM that could be attributed to sulfates. Filters from initial tests with the Baseline fuel and B20 were taken for analysis via ion chromatography. The results of these analyses are summarized below in Table 14.

TABLE 14. SULFATE ANALYSIS RESULTS FOR SELECTED PM FILTERS

Fuel			Test Cycle					
			CFTP	**H1FTP**	**H2FTP**	**H3FTP**	**LLC**	**RMC**
BL			**12/12/2022**	**12/12/2022**	**12/12/2022**	**12/12/2022**	**12/12/2022**	***12/14/2022***
	PM	g/hp-hr	0.0013	0.0020	0.0014	0.0015	0.0030	*0.0029*
		mg	0.0154	0.0232	0.0171	0.0176	0.0507	*0.1627*
	Sulfate	mg	0.000	0.000	0.002	0.000	0.003	*0.110*
	% Sulfate	%	0	0	13	0	7	*68*
B20			**12/13/2022**	**12/13/2022**	**12/13/2022**	**12/13/2022**	**12/13/2022**	***12/13/2022***
	PM	g/hp-hr	0.0027	0.0017	0.0017	0.0018	0.0032	*0.0027*
		mg	0.032	0.020	0.020	0.021	0.053	*0.151*
	Sulfate	mg	*0.097*	*0.046*	0.023	0.014	0.009	*0.080*
	% Sulfate	%	307	232	115	67	18	*53*
BL Post High Temp Regen			**1/26/2023**	**1/26/2023**	**1/26/2023**	**1/26/2023**	**1/26/2023**	**1/26/2023**
	PM	g/hp-hr	0.0023	0.0014	0.0009	0.0014	0.002	0.0005
		mg	0.0266	0.0161	0.0105	0.0164	0.0338	0.0287
	Sulfate	mg	0.000	0.000	0.000	0.000	0.000	0.000
	% Sulfate	%	0	0	0	0	0	0

For the Baseline diesel fuel, the results indicated only a small portion of the PM coming from sulfates, with the exception of the RMC, which had a PM level of 0.003 g/hp-hr that was mostly sulfate. However, as noted earlier, this was likely due to sulfation on the DPF. As a result, the sulfate was re-checked on the BL fuel after the high temperature active regeneration event mentioned earlier. On that check-point, the RMC PM emissions were more in line with expectations at 0.0005 g/hp-hr with little or no sulfate present. All other cycle results were similar from before and after the regeneration event. The B20 fuel was likely affected by the same thing on the RMC-SET cycle, but it was noted that significant sulfate levels were observed on other tests as well. However the B20 sulfate results indicate levels above the recorded PM mass itself, so it is not clear what caused that increase, as elevated levels were not observed in the blanks. The results indicated that the PM emissions for the FTP were primarily sulfate (although they were still very low), except for on the LLC. It was noted that a decreasing level was observed on each successive FTP so it is possible that the change of fuel may have allowed the release of some of the sulfur stored on the DPF. It seems unlikely that the use of B20 would normally result in such an increase when the PM numbers themselves were not significantly different from the Baseline fuel.

4.0 SUMMARY AND CONCLUSIONS

All of the eight CRC test fuels were evaluated in triplicate over the regulated emission cycles for on-highway heavy-duty diesel engines. The tailpipe NO_X results are summarized below in Figure 25, with the hot-start data shown being only for the first hot-start of a given test sequence (used to calculate the composite FTP level). As noted earlier the data indicated that the variation due to fuels other than the B50 was within a range of -2 to +4 mg/hp-hr from EPA 2 certification fuel results of 17 mg/hp-hr. Conventional diesel fuels with higher aromatic content tended to have higher tailpipe NO_X levels. The B50 fuel showed a larger change of +12 mg/hp-hr. The LLC showed similar direction trends, while the RMC-SET demonstrated no tailpipe NO_X sensitivity to fuel changes, despite significant changes observed in engine-out NO_X emissions. All measured NO_X levels were below the 2027 EPA limit values, although the B50 was close to the limit on the FTP.

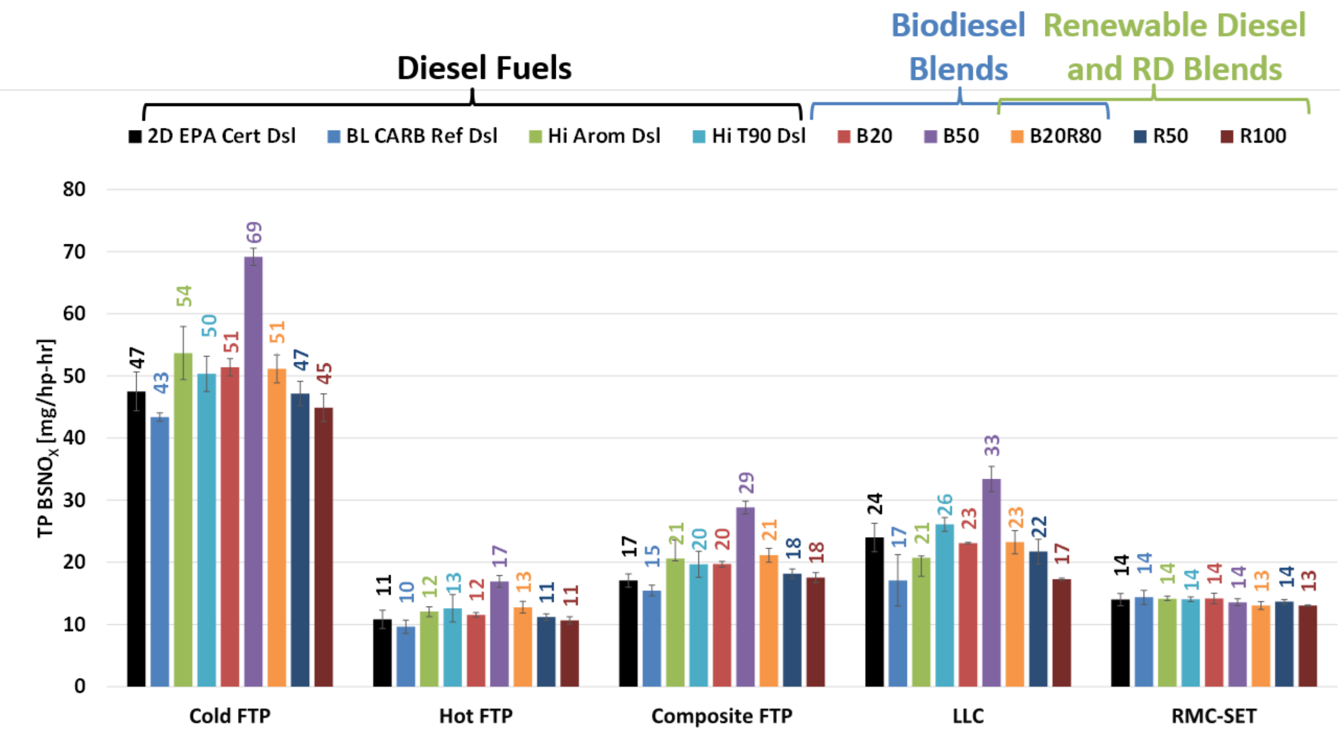

FIGURE 25. SUMMARY OF TAILPIPE NO_X EMISSIONS ON VARIOUS TEST FUELS

Analysis of these trends along with previous field cycle data from the Stage 3 engine for both Development Aged and end-of-life (EOL) DAAAC aged parts suggested that the in-use impact of fuels under in-use conditions would be similar to levels given below in Table 15. Note that in the case of the B50, the impact was always in the direction of increased NO_X.

On average, these analytical results a potential impact of -4 to +3 mg/hp-hr for fuels not including B50 and +5-10 mg/hp-hr for B50. These values are on the order of 5% of the Bin 2 in-use standard of 73 mg/hp-hr for MHD and HHD diesel engines for fuels not including B50, and on the order of 10% for B50. It should be noted that these numbers represent the full range of potential impact from the range of fuels tested, and that actual fuel impacts will likely vary within that range.

TABLE 15. PROJECTED IN-USE NO_X EMISSION IMPACTS FROM FUELS

Field Cycle	Fuels except B50	B50
SNTE	-3 to +3	+10
ACES 5m	-1 to +1	+5
Drayage	-4 to +1	+7
EU-ISC	-2 to +2	+6
Grocery	-4 to +2	+9

Tailpipe PM emissions were generally unaffected by the different fuels, and similar tailpipe HC and CO emissions were also unaffected by the fuels.

Finally the regeneration testing indicated that both B20 and R100 fuels had a significant benefit in terms of reduced soot loading rates on the DPF. This would likely lead to a lower active regeneration frequency for the DPF under part-load transient duty cycles. This would in turn have several benefits, including a lower NO_X UAF, less fuel consumption associated with active regeneration, and possibly improved durability of the downstream SCR system due to less high temperature exposure (although this last potential benefit would need to be verified via long-term durability experiments).

It was generally observed that the renewable diesel fuel derived from HVO (R100) was a very high quality diesel fuel that had beneficial impacts on nearly all aspects of engine performance. This included good engine performance and improved combustion characteristics, NO_X emissions near the lower end of the variation range, lower mass fuel consumption rates (although volumetric fuel consumption is increased due to lower density), lower measured tailpipe CO_2 emissions, and lower engine-out soot rates likely leading to less frequent active regenerations. Given that this fuel is made from a renewable feedstock which also has substantial upstream CO_2 emission benefits, this fuel would seem to be excellent choice for future diesel fueled engine platforms. It is also likely that the renewable diesel would be a useful blend stock that could potentially mitigate some of the observed impacts of higher biodiesel blends such as B50.

The results of this program provide a thorough characterization of short-term fuel impacts on a representative Low NO_X test engine using technologies likely to be deployed in MY 2027 and beyond. It is clear that there is a role for fuels to play in helping to enable the success of future emission control systems and in helping to reduce NO_X and GHG emissions from diesel engines.

5.0 REFERENCES

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APPENDIX A – TEST FUEL ANALYTICAL DATA

TABLE A-16. FUEL PROPERTY DATA

Fuel			2D	BL	Hi Arom Diesel	Hi T90 Diesel	B20	B50	B20R80	R50	R100
Fuel Code			Tk 37	EM11300	EM11301	EM11302	EM11303	EM11304	CDF11268	CDB11357	CDF11267
Fuel Description			EPA 2D Certification Grade Diesel	CARB Reference Diesel	Hi Aromatic Diesel	Hi T90 Hi Aromatic Diesel	B20 with HiT90 Base	B50 with HiT90 Base	B20 with R100 Base	50% R100 with HiT90 Base	Renewable Diesel (from HVO)
ASTM Method											
D2500	Cloud Point	deg. C	-39	-28	-28	-27	-25	-14	-6	-19	-12
D4052	API Gravity	--	36.6	37.29	35.37	34.84	33.85	31.81	44.63	41.78	49.31
	Specific Gravity	--	0.8418	0.8383	0.8479	0.8507	0.8557	0.8664	0.8034	0.8166	0.7826
	Density @ 15°C	g/mL	0.8410	0.8375	0.8471	0.8498	0.8549	0.8656	0.8031	0.8162	0.7823
D445	Viscosity at 40°C	cSt	2.20	2.90	1.90	2.37	2.60	3.14	3.27	2.72	3.18
D4809	Heat of Combustion										
	GROSS	BTU/lb	19622	19808	19376	19417	19049	18351	19588	19784	20312
	GROSS	MJ/kg	45.64	46.073	45.068	45.165	44.307	42.685	45.562	46.016	47.246
	GROSS	cal/g	10900.9	11004.4	10764.4	10787.4	10582.6	10195.1	10882.2	10990.8	11284.4
D4809	Heat of Combustion										
	NET	BTU/lb	18432	18564	18216	18258	17891	17224	18256	18501	18922
	NET	MJ/kg	42.873	43.181	42.369	42.468	41.614	40.062	42.465	43.033	44.013
	NET	cal/g	10240	10313.6	10119.7	10143.2	9939.4	9568.7	10142.5	10278.2	10512.2
D452	Ash Content	mass %	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
D5186	Total Aromatics by SFC										
	Total Aromatics	mass %	31.4	8.4	34.0	34.3	27.4	17.2	0.3	18.1	0.3
	Mono-aromatics	mass %	21.5	7.1		30.4	24.3	15.2	0.3	16.1	0.3
	Polynuclear Aromatics	mass %	9.9	1.3		3.9	3.1	1.9	0	1.9	0
D5453	Sulfur by UV	ppm	11.7	12	13.7	14.4	11.3	8.1	<0.5	6.8	<0.5
D6079	Lubricity by HFRR										
	Wear Scar Diameter	micron	388	600	260	290	190	190	170	250	600
D613	Cetane Number	--	46.6	52	40.3	45.7	44.5	47.1	73.2	63	>74.8
D7371	Biodiesel Content by FTIR										
	Volume % biodiesel	vol%	0.0	0.0	4.6	4.6	21.2	49	20.13	2.2	<1.0
D7525	Oxidation Stability (RSSOT)										
	Induction Time	minutes	n/a	n/a	n/a	n/a	n/a	n/a	62	88	257
D7545	Oxidation Stability (RSSOT)										
	Induction Time	minutes	n/a	146	46	50	47	34	53	82	205
D86	Distillation										
	IBP	Deg. F	346	385	366	385	386	393	399	379	383
	5%	Deg. F	388	417	394	410	415	429	508	423	495
	10%	Deg. F	404	426	400	415	422	444	528	442	515
	20%	Deg. F	428	443	410	428	439	476	543	466	532
	30%	Deg. F	449	458	418	440	456	525	552	491	540
	40%	Deg. F	469	477	429	459	482	571	558	515	545
	50%	Deg. F	487	497	445	484	515	604	564	532	549
	60%	Deg. F	506	521	469	513	552	621	570	545	552
	70%	Deg. F	527	548	499	543	588	629	577	556	556
	80%	Deg. F	551	578	532	583	616	634	589	568	560
	90%	Deg. F	583	609	582	620	632	640	609	585	567
	95%	Deg. F	613	630	618	639	643	662	631	604	577
	FBP	Deg. F	650	640	636	649	650	655	651	637	605
	Recovered	mL	98.4	97.8	97.6	97.8	97.5	97.8	98.3	98	97.7
	Residue	mL	0.3	1.3	1.4	1.4	1.4	1.4	1.3	1.2	1.3
	Loss	mL	1.3	0.9	1.0	0.8	1.1	0.8	0.4	0.8	1
D93	Flash Point Closed Cup										
	Flash Point	Deg. F	150	181	165	178	183	199	164	168	168
	Flash Point	Deg. C	66	83	74	81	84	93	74	0	76
D5291	Carbon	mass %	86.46	85.23	86.22	85.97	84.28	81.45	82.84	84.69	83.98
	Hydrogen	mass %	13.04	13.63	12.72	12.71	12.69	12.36	14.26	13.75	14.64
Calc	Oxygen	mass %	0.0	0.0	0.5	0.5	2.2	5.5	2.2	0.2	0.0

TABLE A-17. RENEWABLE FUEL BULK MODULUS DATA

Bulk Modulus of Renewable diesel (R100) derived from HVO		
CDF-11267		
Temperature (°C)	Pressure (psig)	Bulk Modulus (psi)
32.1	2773	220726
48.5	2755	202548
69.6	2777	179987

Bulk Modulus of R80/B20 (renewable portion is same R100)		
CDF-11268		
Temperature (°C)	Pressure (psig)	Bulk Modulus (psi)
30	2753	233153
49.6	2755	207135
69.7	2758	186131

TABLE A-18. ADDITIONAL HC ANALYSES OF RENEWABLE DIESEL FUELS BY ASTM D2425

CRC RW-120 Analyses of Renewable Diesel Fuels and Blends				
Fuel Description			**Renewable diesel (R100) derived from HVO**	**R50, 50/50 vol% Blend of R100 Diesel (CDF-11267) and High T90 Diesel (EM-11302)**
Fuel Code			CDF-11267	CDB-11357
ASTM Method	**Test Request**	**Test Units**	**Results**	**Results**
D2425	Hydrocarbon Types (Mass Spectrometry)			
	Paraffins	weight	94.3	60.6
	Monocycloparaffins	weight	5.1	14.2
	Dicycloparaffins	weight	0.6	7.9
	Tricycloparaffins	weight	0.0	1.1
	Total Naphthenes	weight	5.7	23.2
	Total Saturates	weight	100.0	83.8
	Alkylbenzenes	weight	0.0	7.4
	Indans/Tetralins	weight	0.0	3.5
	Indenes (CnH2n-10)	weight	0.0	1.4
	Naphthanlene	weight	0.0	0.0
	Naphthalenes, Alkyl	weight	0.0	2.2
	Acenaphthenes (CnH2n-14)	weight	0.0	0.8
	Acenaphthylenes (CnH2n-16)	weight	0.0	0.6
	Ttrcyclic Aromatics (CnH2n-18)	weight	0.0	0.3
	Total PNA'S	weight	0.0	3.8
	Total Aromatics	weight	0.0	16.2

TABLE A-19. ADDITIONAL HC ANALYSIS OF RENEWABLE FUELS AND BLENDS BY ASTM D8368

Renewable diesel (R100) derived from HVO					
Fuel Code CDF-11267					
Sample Code FLRD-4446					
Mass %					
Name	**Run 1**	**Run 2**	**Run 3**	**Avg**	**%RSD**
Total Saturates	99.98	99.98	99.88	99.95	0.05
Total Aromatics	0.023	0.015	0.016	0.018	19.0
Total Mono-Aromatics	0.014	0.015	0.016	0.015	5.62
Total Di-Aromatics	0.003	0	0	0.001	141.4
Total Tri(+)-Aromatics	0.006	0	0	0.002	141.4
Total PAHs	0.009	0	0	0.003	141.4
Total FAMEs	0	0	0.105	0.035	141.4
Volume %					
Name	**Run 1**	**Run 2**	**Run 3**	**Avg**	**%RSD**
Total Saturates	99.98	99.99	99.89	99.95	0.05
Total Aromatics	0.020	0.014	0.015	0.016	15.6
Total Mono-Aromatics	0.013	0.014	0.015	0.014	5.52
Total Di-Aromatics	0.003	0	0	0.001	141.4
Total Tri(+)-Aromatics	0.004	0	0	0.001	141.4
Total PAHs	0.007	0	0	0.002	141.4
Total FAMEs	0	0	0.098	0.033	141.4
Mole %					
Name	**Run 1**	**Run 2**	**Run 3**	**Avg**	**%RSD**
Total Saturates	99.96	99.97	99.88	99.94	0.04
Total Aromatics	0.040	0.031	0.034	0.035	11.1
Total Mono-Aromatics	0.030	0.031	0.034	0.032	4.81
Total Di-Aromatics	0.004	0	0	0.001	141.4
Total Tri(+)-Aromatics	0.006	0	0	0.002	141.4
Total PAHs	0.010	0	0	0.003	141.4
Total FAMEs	0	0	0.087	0.029	141.4

R80/B20 (renewable portion is same R100)					
Fuel Code CDF-11268					
Sample Code FLRD-4447					
Mass %					
Name	**Run 1**	**Run 2**	**Run 3**	**Avg**	**%RSD**
Total Saturates	77.20	76.87	76.92	77.00	0.19
Total Aromatics	0.141	0.131	0.140	0.137	3.17
Total Mono-Aromatics	0.140	0.129	0.137	0.135	3.52
Total Di-Aromatics	0.000	0.002	0	0.001	141.4
Total Tri(+)-Aromatics	0.001	0.000	0.002	0.001	71.8
Total PAHs	0.001	0.002	0.002	0.002	36.0
Total FAMEs	22.66	23.00	22.94	22.87	0.66
Volume %					
Name	**Run 1**	**Run 2**	**Run 3**	**Avg**	**%RSD**
Total Saturates	79.05	78.75	78.79	78.86	0.17
Total Aromatics	0.132	0.123	0.131	0.129	3.18
Total Mono-Aromatics	0.132	0.121	0.129	0.127	3.49
Total Di-Aromatics	0.000	0.002	0	0.001	141.4
Total Tri(+)-Aromatics	0.001	0.000	0.002	0.001	74.3
Total PAHs	0.001	0.002	0.002	0.001	37.1
Total FAMEs	20.81	21.13	21.08	21.01	0.66
Mole %					
Name	**Run 1**	**Run 2**	**Run 3**	**Avg**	**%RSD**
Total Saturates	81.43	81.15	81.18	81.25	0.16
Total Aromatics	0.169	0.160	0.181	0.170	5.13
Total Mono-Aromatics	0.168	0.158	0.179	0.168	5.14
Total Di-Aromatics	0.000	0.002	0	0.001	141.4
Total Tri(+)-Aromatics	0.001	0.000	0.002	0.001	71.8
Total PAHs	0.001	0.002	0.002	0.002	35.4
Total FAMEs	18.40	18.69	18.64	18.58	0.69

R50, 50/50 vol% Blend of R100 Diesel (CDF-11267) and Fuel 3 High T90 Diesel (EM-11302)					
Fuel Code CDF-11357					
Sample Code FLRD-4448					
Mass %					
Name	**Run 1**	**Run 2**	**Run 3**	**Avg**	**%RSD**
Total Saturates	80.32	81.38	80.20	80.63	0.66
Total Aromatics	17.11	16.10	17.28	16.83	3.10
Total Mono-Aromatics	15.66	14.43	15.56	15.21	3.66
Total Di-Aromatics	1.44	1.67	1.704	1.60	7.30
Total Tri(+)-Aromatics	0.009	0.002	0.024	0.012	78.9
Total PAHs	1.45	1.67	1.73	1.62	7.47
Total FAMEs	2.57	2.52	2.52	2.54	0.94
Volume %					
Name	**Run 1**	**Run 2**	**Run 3**	**Avg**	**%RSD**
Total Saturates	82.03	83.06	81.94	82.35	0.62
Total Aromatics	15.63	14.65	15.77	15.35	3.24
Total Mono-Aromatics	14.47	13.31	14.38	14.05	3.75
Total Di-Aromatics	1.15	1.34	1.366	1.28	7.41
Total Tri(+)-Aromatics	0.006	0.002	0.018	0.009	80.3
Total PAHs	1.16	1.34	1.38	1.29	7.58
Total FAMEs	2.34	2.29	2.29	2.31	0.98
Mole %					
Name	**Run 1**	**Run 2**	**Run 3**	**Avg**	**%RSD**
Total Saturates	75.26	76.16	75.03	75.48	0.65
Total Aromatics	22.95	22.08	23.22	22.75	2.13
Total Mono-Aromatics	20.93	19.80	20.89	20.54	2.55
Total Di-Aromatics	2.01	2.28	2.306	2.20	6.16
Total Tri(+)-Aromatics	0.008	0.002	0.024	0.011	80.6
Total PAHs	2.01	2.28	2.33	2.21	6.27
Total FAMEs	1.80	1.76	1.75	1.77	1.10