THESIS

EVALUATION OF ETHANOL SUBSTITUTION IN A COMPRESSION IGNITION ENGINE

Submitted by

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ABSTRACT

EVALUATION OF ETHANOL SUBSTITUTION

IN A COMPRESSION IGNITION ENGINE

Heavy duty compression ignition engines rely on advanced emission control strategies to mitigate regulated emissions in compliance with requirements set by the Environmental Protection Agency. These strategies add significant cost and complexity to engine design. Previous work identified that a diesel-ethanol dual fuel combustion technique may be able to reduce diesel fuel consumption and supplement current emission control methods. The substitution of diesel fuel with a renewable, U.S. based fuel such as corn ethanol would also improve US energy security. A review of diesel-ethanol dual fuel combustion identified five possible methods of diesel-ethanol dual fuel combustion. They were ethanol-diesel emulsions, ethanol-diesel-additive blending, twin direct injection of ethanol and diesel, ethanol fumigation of intake air with standard diesel fuel injection, and full substitution of diesel with ethanol. Analysis of ethanol-diesel emulsions and ethanol-diesel-additive blending concluded that only low volumes of ethanol (<10%) could be blended in diesel fuel before the two fuels were immiscible. However, analysis using ternary phase diagrams showed that additives such as B100 biodiesel could be used to extend the substitution limit significantly such that at 25°C mixtures of 80% 200 proof ethanol, 10% B100 biodiesel, and 10% off-road diesel were visibly miscible. Miscible mixtures containing high volumes of ethanol underwent further analysis, which showed that these fuels were not suitable drop in replacements for diesel fuel due to poor cold flow properties.

Based on fuel blending analysis and previously published literature ethanol fumigation of intake air was selected for an on-engine demonstration using a Cummins 6.7L QSB Tier 4 Final engine. Three ethanol based fuels were selected for this dual fuel combustion work: 200 proof ethanol, 190 proof ethanol, and a blend of 15% E0 gasoline and 85% 200 proof ethanol. Pre and post aftertreatment emission

data and high speed combustion data were collected while operating the engine at ISO 8178 test points C1-7, C1-3, and C2-4. The maximum diesel substitution at each test point was similar among the three test fuels. and at moderate to high engine loads diesel substitution was limited to 25% and 39%, respectively due to engine knock . At low engine loads substitution was limited to 25% by exhaust emission requirements. Premixed ethanol combustion increased brake specific efficiency at moderate and high engine loads by 3% and 3.2%, respectively, but reduced efficiency at low engine loads by 1.4%. Finally, although the complete ISO 8178 test map was not completed the Tier 4 Final after treatment system was able to reduce ethanol premixed combustion emissions to at or below the diesel baseline emissions at nearly every test point.

ACKNOWLEDGEMENTS

I would like to recognize people and groups who supported during the work presented in this Thesis. First, Dr. Daniel Olsen for his willingness to allow me to work in his research group, support over the course of the past two years of work, and his mentorship during my entire education. Second, the Colorado Corn Administrative Committee, Front Range Energy, and Growth Energy who supported this work by funding not only the engine test days but also the installation and commissioning of a new engine test cell. I would also like to thank Dr. Lyle Kocher, technical adviser in the Advanced Engine Development group of Cummins for his generous donation of a new engine, after treatment system, and technical support. Paul Odneal from this Kistler Group donated the in cylinder pressure transducers and replacement extension cables. Matt Snow from Snow Performance who donated the ethanol injection kit and gave technical support while installing the system. The Powerhouse staff – Mark, Kirk, and James – who guided me through months of troubleshooting and set up of the engine test cell and advised me every step of the way. I would also like to thank many others who assisted me – Matt, Marco, Robbie, Brett, and Will. My parents Steve and Deanne your encouragement, support, and prayers during the past two years has been felt every day. Thank you. Finally, my Lord and Savior Jesus Christ, without which none of this would have been possible. ‘For from Him and through Him and for Him are all things. To Him be the glory forever! Amen’ – Romans 11:36.

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ABREVIATIONS AND SYMBOLS

Term	Abbreviation
Carbon Dioxide	CO_2
Carbon Monoxide	CO
Coefficient of Variation	COV
Cold Filter Plug Point	CFPP
Crank Angle Degrees	CAD
Degrees After Top Dead Center	°ATDC
Degrees Before Top Dead Center	°BTDC
Derived Cetane Number	DCN
Diesel Exhaust Fluid	DEF
Diesel Oxidation Catalyst	DOC
Engine Control Unit	ECU
Exhaust Gas Recirculation	EGR
Fast Fourier Transform	FFT
Flame Ionization Detector	FID
Fourier Transform Infrared	FTIR
Fuel Ignition Tester	FIT
High Pressure Direct Injection	HPDI
Higher Heating Value	HHV
Indicated Mean Effective Pressure	IMEP
Knock Index	KI
Main Start of Injection	mSOI
Mass Fraction Burned	MFB
Net Heat Release Rate	NHRR
Non-Methane Hydrocarbon	NMHC
Oides of Nitrogen	NO_x
Oxygen	O_2
Particulate Matter	PM
Pressure Rise Rate	PRR
Research Octane Number	RON
Revolutions per Minute	rpm
Selective Catalytic Reduction	SCR
Total Hydrocarbons	THC

CHAPTER 1
INTRODUCTION

1.1. MOTIVATION

According to the U.S. Energy Information Administration total diesel fuel retail sales has increased nearly 30% from 1984 to 2013. During that time the number one consumer of diesel fuel was the on-highway vehicle market which, on average, consumed 53% or 30 billion gallons of all diesel fuel each year. The agriculture and railroad markets ranked second and third, respectively, and consumed 6.13% (3.2 billion gallons) and 5.91% (3.1 billion gallons) of all diesel fuel sold annually [1]. The U.S. Energy Information Administration also tracks diesel fuel retail prices and has records of prices dating back to March, 1994. Figure 1 shows that from March, 1994 to May, 2015 diesel fuel retail price per gallon has risen nearly 230%, to an average national cost in January 2017 of $2.56 per gallon [2] with a peak U.S. retail price of $4.76 per gallon occurring in July of 2008.

Figure 1. Average U.S. retail price of on-road No. 2 diesel fuel [17]

During this same period exhaust emissions standards for heavy duty compression ignition engines have become more stringent. Figure 2 shows this trend of engine emission limits for both particulate matter and NO_x emissions which culminates in the current Tier 4 Final emissions requirements. In response to more stringent emissions standards engine manufacturers developed emission reduction techniques to reduce emissions of NO_x (oxides of nitrogen), PM (particulate matter), CO (carbon monoxide), and NMHC (non-methane hydrocarbons). These techniques include systems such as exhaust gas recirculation, oxidation catalysts, particulate filters, selective catalytic reduction systems, and ammonia injection systems. Due to the inherent low particulate matter emission and low temperature combustion of ethanol fuel, a diesel-ethanol dual fuel combustion approach may be a viable method of reducing engine exhaust emissions or replacing exhaust after treatment technologies. This approach would be advantageous to engine manufacturers while also serving to expand the ethanol fuel market, increase renewable fuel usage, and lower the operating costs of compression ignition engines.

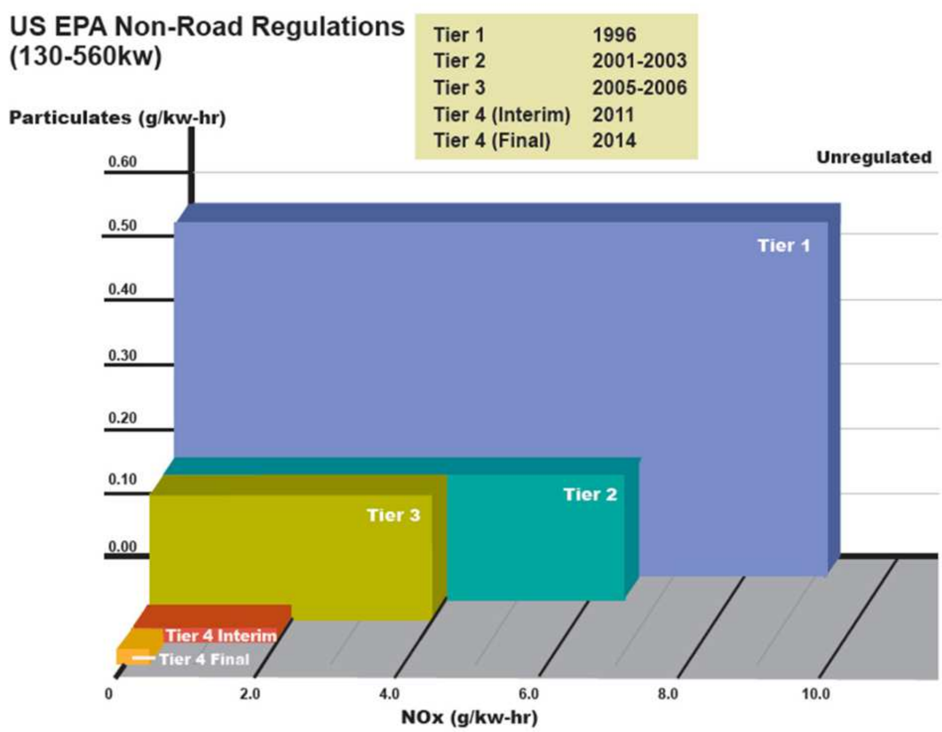

Figure 2. EPA engine emission regulations trend for non-road vehicles [18]

1.2. LITERATURE REVIEW

A detailed review of previously published literature on the research topic was conducted to first, identify methods by which ethanol has been previously used in a compression ignition engine and second, to evaluate the feasibility of these methods in order to provide direction for an on engine laboratory demonstration of these methods. Five methods of diesel-ethanol dual fuel combustion were identified during the literature review. They are ethanol-diesel emulsions, ethanol-diesel-additive blending, twin direct injection of ethanol and diesel, ethanol fumigation of intake air with standard diesel fuel injection, and full substation of diesel with ethanol.

1.2.1. Ethanol-Diesel Emulsions

Adding ethanol to diesel fuel significantly affects many important fuel properties including, but not limited to, lubricity, flash point, cetane number, energy content, and viscosity [3,4,5,6]. In addition to the effects ethanol has on fuel properties, blend stability is also affected when combining these two fuels. Blend stability is negatively impacted at lower temperatures and as water is added to the blend [3,5,6,7]. Hansen et al. [3] noted that below 10°C the anhydrous ethanol and diesel fuel will separate. However, separation can be avoided by adding emulsifiers or co-solvents to the blended fuel. In 1984 SAE published ‘Alcohols in diesel engines: a review’ [14] which outlined the effects that emulsifiers have on fuel properties and engine performance. The author stated that the major drawbacks of emulsifiers are their cost and poor low temperature physical properties. Further, the viscosity of an emulsified blend increases substantially at temperatures approaching 0°C.

Due to the low cetane number of ethanol, an ethanol-diesel blend has a cetane number lower than standard diesel. Increased ignition delay results in more complete mixing of the fuel and air in the combustion chamber and higher heat release rates during the combustion process [3,7]. At high engine loads increased ignition delay has a strong tendency to increase maximum cylinder pressure and pressure rise rate (PRR), and can lead to engine knocking. [9,13]

Fuel lubricity and viscosity are also lowered when ethanol is added to diesel fuel. This is concerning because diesel fuel injection systems rely on fuel for the lubrication of many components, and a modified fuel viscosity affects spray penetration, pattern, and atomization during injection into the combustion chamber. Lower fuel viscosity may promote higher unburned hydrocarbon emissions in the following two ways. First, a lower viscosity fuel more readily leaves the diesel injector pintle during the exhaust stroke and can be exhausted from the combustion chamber with exhaust gases. Second, a lower viscosity fuel may have a larger spray penetration depth and impinge on the cylinder wall where it remains unburned and is again exhausted with other combustion products. [3,4,5,6]

Perhaps the most concerning property of ethanol-diesel blends are their flammability limits and flash point. Flammability limits define the maximum and minimum concentration of combustible vapor in air at a specified temperature that will propagate a flame after required ignition energy is provided [3]. Flash point is defined as the lowest temperature at which the vapor pressure of a liquid is sufficient to produce a flammable mixture in the air above the liquid surface within a vessel [3]. Coronado et al. [8] found the upper and lower flammability limits of anhydrous ethanol at 298K and atmospheric pressure to be approximately 14% and 3.5% vapor concentration, respectively. Hansen et al. [3] cited research done by Battelle et al. that showed that 10%, 15%, and 20% ethanol in diesel blends have similar flammability limits and flash point as 200 proof anhydrous ethanol. Thus, in terms of safety, ethanol-diesel blends should be treated similar to 200 proof anhydrous ethanol. Further, ethanol is considered a Class I fuel by the National Fire Protection Agency because its flash point is below 37.8°C, but diesel fuel is considered a Class II fuel so the addition of ethanol to diesel fuel would change the fuel classification from Class II to Class I requiring changes in storage and system design [3].

1.2.2. Ethanol-Diesel-Additive Blends

Additives in ethanol-diesel blends attempt to address some of the issues that arise when blending ethanol and diesel. For example, Tutak et al. [9] used E85 to improve the low temperature properties and assist with cold starting of ethanol-diesel blends, and Selvan et al. [10] used biodiesel to prevent phase separation of ethanol and diesel. In addition to phase separation, biodiesel can also act as an overall fuel cetane number improver due to its high cetane number (approximately 59) [11].

1.2.3. Twin Direct Injection

No research papers specific to twin direct injection of diesel and ethanol were found during the literature review. However, the fuel injector technology to accommodate this concept is commercially available for diesel-natural gas engines**.** Caterpillar [12] offers a high pressure direct injection (HPDI) fuel injector designed to inject both diesel fuel and natural gas into the combustion chamber. The HPDI injector is meant to replace the standard fuel injector, and is designed to inject a large amount of natural gas into the cylinder while injecting only a small portion of diesel fuel. The diesel fuel acts as an ignition source for the rest of the fuel. Further investigation into this technology would be required to understand if it could also be used for ethanol-diesel twin direct injection.

1.2.4. Ethanol Fumigation of Intake Air

Fumigating engine intake air with ethanol takes advantage of the cooling effects of ethanol while eliminating the challenge of creating a stable blend of ethanol and diesel. A drawback of this technique is that several engine system modifications must be made. First, a separate fuel tank must be used to safely store ethanol before it is injected into the air intake manifold. Second, new fuel lines need to be installed and one or more fuel injectors plumbed into the air intake manifold. A single injector can be installed in the intake manifold, or multiple injectors can be installed upstream of the intake ports. In the literature reviewed no attempt was made to install fuel injector(s) upstream of a turbocharger. Finally, an injection control unit must be installed to control the injection rate and timing of the ethanol injection while also interfacing with the existing engine control unit.

The author of ‘Alcohols in diesel engines: a review’ [14] discussed the advantages and disadvantages of air intake fumigation in detail. The paper states that alcohol delivery must be reduced at low loads to prevent flame quenching and misfire and at high loads to prevent preignition and engine knock. In the medium load range, up to 50% of the fuel energy can be derived from alcohol. The paper concludes that in general alcohol fumigation causes increased unburned hydrocarbon and carbon monoxide emissions while reducing NO_x emissions. Unburned hydrocarbon emissions increased because of the quench layer of unburned fumigated alcohol present. There is no quench layer with diesel fuel injection alone because combustion is droplet diffusion controlled and fuel is completely surrounded by air. Carbon monoxide emissions tend to increase because combustion of the alcohol is similar to homogeneous charge spark ignited combustion rather than being droplet diffusion controlled.

1.2.5. 100% Ethanol Substitution

Full substitution of diesel by using ethanol is not feasible in compression ignition engines due to the poor ignition properties of ethanol compared to diesel. During the literature review no research was found that attempted a 100% ethanol substitution in a diesel engine.

1.3 LITERATURE REVIEW SUMMARY

Of the five methods of ethanol-diesel blending identified ethanol fumigation of intake air and ethanol-diesel-additive blending are feasible methods of using ethanol in a diesel engine. Of these two methods, ethanol fumigation of intake air is preferred due to its expected high ethanol substitution rates at a wide range of ambient temperatures, expected reduced NO_x and particulate matter emissions, and negligible fuel miscibility issues.

CHAPTER 2
FUEL PROPERTY ANALYSIS

Fuel property tests were performed for select ethanol-diesel blends. The purpose of the testing was to gain more insight into the use of various fuel blends, confirm conclusions derived from the literature, and gather additional fuel property data to be used in future engine testing.

2.1 MISCIBILITY

The miscibility of diesel and various proofs of ethanol were studied using the liquid – liquid ternary phase diagram method. In this method diesel, ethanol, and a blending agent were mixed together to form a 5 mL sample. Volumes of fuel were measured using 1 mL and 0.2 mL Eppendorf reference liquid injectors. Volume ratios of the three fuels were varied until a total of 66 different fuel combinations were mixed. After the samples were mixed they were allowed to come to equilibrium for a period of 48 hours before results were recorded. Cold temperature tests were conducted in a commercially available refrigerator and freezer at 1.5 and -17°C, respectively. Samples were stored at each temperature for a period of 24 hours before results were documented. The liquid – liquid ternary phase diagram results are categorized into immiscible, homogeneous, and solid results. Homogeneous mixtures are defined as being similar throughout, and immiscible mixtures are defined as two fluids having a clear, distinguishable boundary. Solid results were achieved due to the test temperatures being below the freezing point of some test fuels.

Figure 3. (L to R) Homogeneous, Immiscible, Heterogeneous, Solid Mixtures

Initially, two different blending fluids were used to increase the blend stability of diesel and ethanol. From the reviewed literature Span 80 and B100 biodiesel were identified as viable fluids and were used to blend 200 proof ethanol and diesel. At 25°C the data showed B100 biodiesel to be a better blending fluid due to fewer immiscible blends, but both blending fluids allowed up to 80% v/v 200 proof ethanol to be blended with diesel fuel. When cooled to 1.5° C both blending fluids again allowed up to 80% v/v 200 proof ethanol to be blended with diesel. When further cooled to -17° C ethanol, diesel, biodiesel blends containing more than 30% biodiesel were solid, and only 100% diesel and 100% ethanol were homogeneous fluids. At -17° C blends of Span 80, 200 proof ethanol, and diesel were 2 phase when containing less than 30% v/v Span 80 with the exception of two blends. The highest homogeneous ethanol substitution occurred at a blend of 40% ethanol, 40% diesel, and 20% Span 80. Figures 4 - 6 show the ternary phase diagrams for Span 80, ethanol, and diesel fuel at 25, 1.5, and -17° C, respectively.

Figures 7 – 9 represent ternary phase diagrams for B100 biodiesel, 200 proof ethanol, and diesel fuel, respectively. Additional ternary phase diagram studies were conducted using lower proof ethanol, diesel fuel, and B100 biodiesel as a blending agent. The lower ethanol proof significantly decreased the blending performance of biodiesel. In contrast to blends containing 200 proof ethanol at room temperature, blends containing 190 proof ethanol at room temperature were nearly all immiscible blends. Homogeneous blends were only achieved using 90% biodiesel. The highest ethanol utilization was found at a blend of 60% 190 proof ethanol, 30% biodiesel, and 10% diesel. Thus, the addition of water to ethanol decreases the blend stability of ethanol, diesel, and biodiesel blends. Blend stability was further decreased when blends containing 190 proof ethanol were cooled to 1.5° C. At this temperature only a blend of 10% 190 proof ethanol, 10% diesel, and 80% biodiesel appeared to be homogeneous. When samples of this mixture were further cooled, all blends containing more than 40% biodiesel were in a solid state while the remaining blends were split between solid and immiscible results. Figures 10-12 detail ternary phase diagrams for blends containing B100 biodiesel and 190 proof ethanol.

Blends containing 170 proof ethanol further confirmed the negative effect that water has on blends of ethanol, diesel, and biodiesel. Figure 13 details this, showing that all blends containing 170 proof ethanol were immiscible at 25° C. Similar results were achieved at 1.5° C in that all blends containing ethanol were immiscible save one blend which was a heterogeneous mixture. Finally, when these samples were cooled to -17° C all blends containing more than 40% biodiesel were in a solid state while all other blends yielded either immiscible or solid results. After 255 fuel blends were evaluated at 25°C, 1.5°C, and -17°C the results showed that two blends containing 200 proof ethanol and 1 blend containing 190 proof ethanol were able to achieve high ethanol substitution rates while remaining homogeneous. A blend of 80% 200 proof ethanol, 10% B100 biodiesel, and 10% diesel appeared to be a homogeneous mixture at 25° and 1.5°C. Similarly, a blend of 80% 200 proof ethanol, 10% Span 80, and 10% diesel appeared to be homogeneous at these temperatures. Finally, a blend containing 60% 190 proof ethanol, 30% B100 biodiesel, and 10% diesel remained a homogeneous mixture at 25°C. Each of these blends optically appeared as homogeneous mixtures and may be a viable replacement for diesel fuel during seasons of warm weather. However, according to ASTM D975 section X5 the average 10th percentile minimum temperatures for November through March in Colorado are -14.4°C and -22.6°C for the east and west portions of the state, respectively. Therefore, these fuels would not be viable for these months. Further research of fuel properties such as viscosity, cetane number, CFPP, and lubricity. for these blends is required. Due to time constraints fuel properties and liquid-liquid ternary phase diagrams for E85 fuel were not conducted. Additionally, the reviewed literature did not address the feasibility of diesel and E85 fuel blends. Future development and analysis of liquid – liquid ternary phase diagrams using B100 biodiesel, diesel, and E85 fuel blends may yield new fuel blends for further investigation.

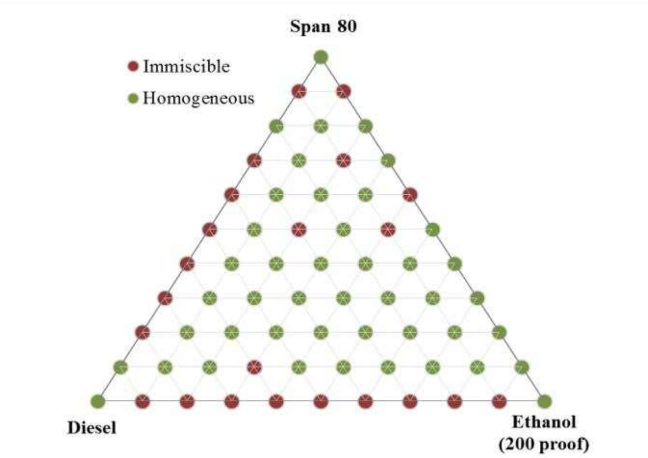

Figure 4. Ternary Phase Diagram (25°C)

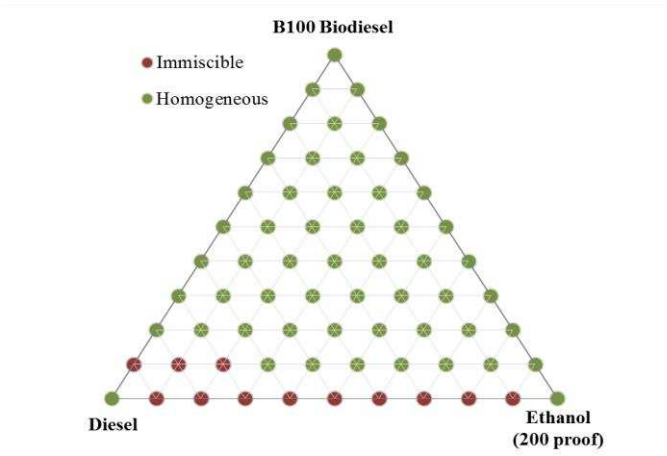

Figure 7. Ternary Phase Diagram (25°C)

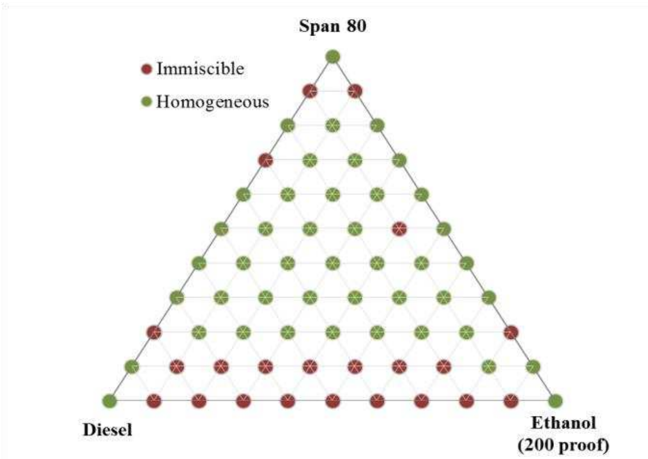

Figure 5. Ternary Phase Diagram (1.5°C)

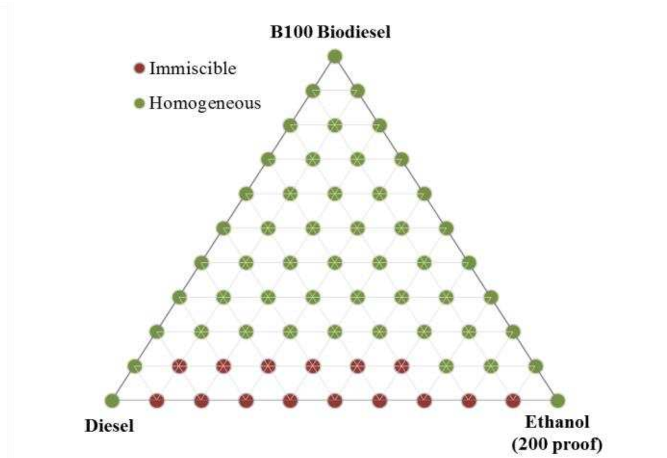

Figure 8. Ternary Phase Diagram (1.5°C)

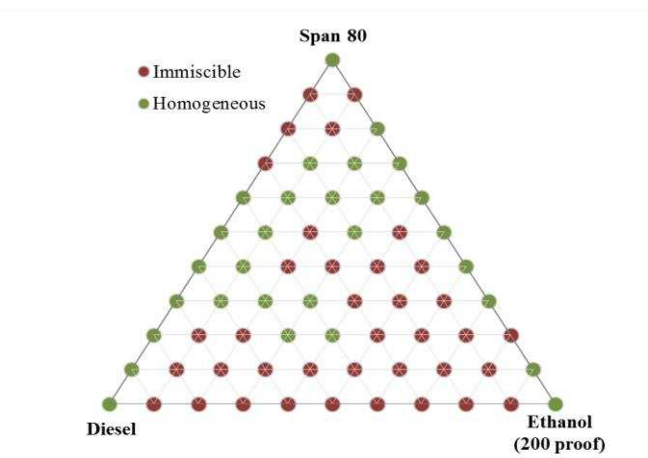

Figure 6. Ternary Phase Diagram (-17°C)

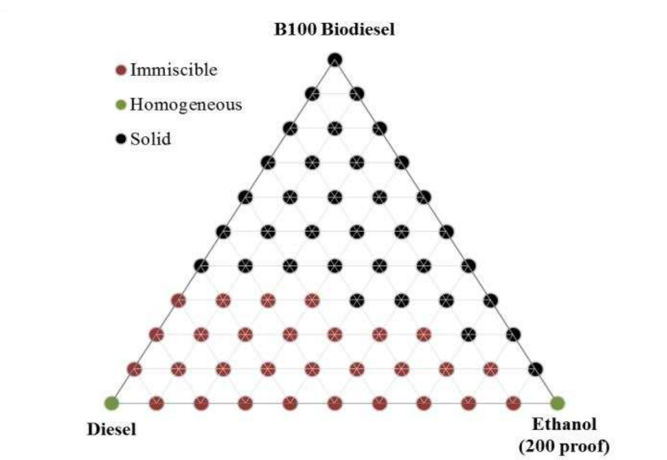

Figure 9. Ternary Phase Diagram (-17°C)

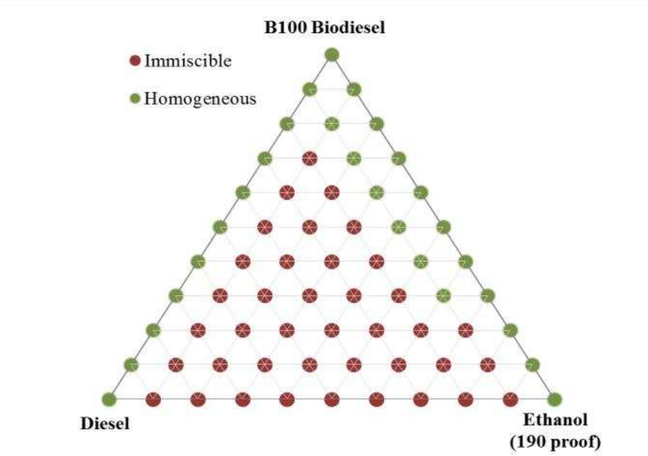

Figure 10. Ternary Phase Diagram (25°C)

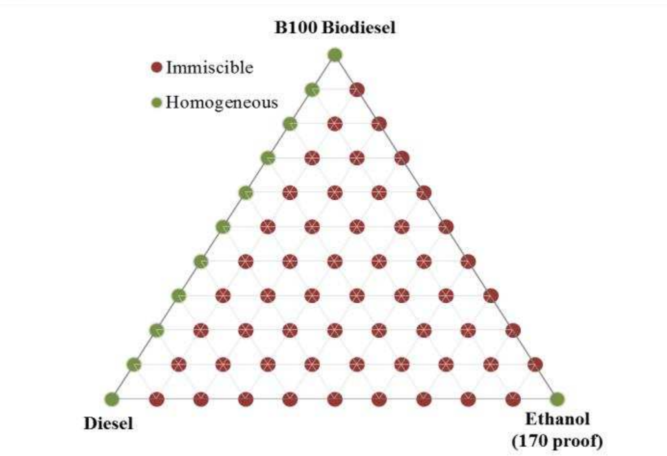

Figure 13. Ternary Phase Diagram (25°C)

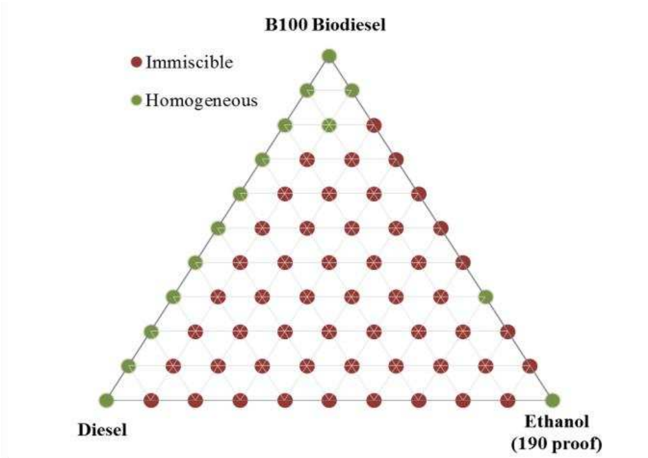

Figure 11. Ternary Phase Diagram (1.5°C)

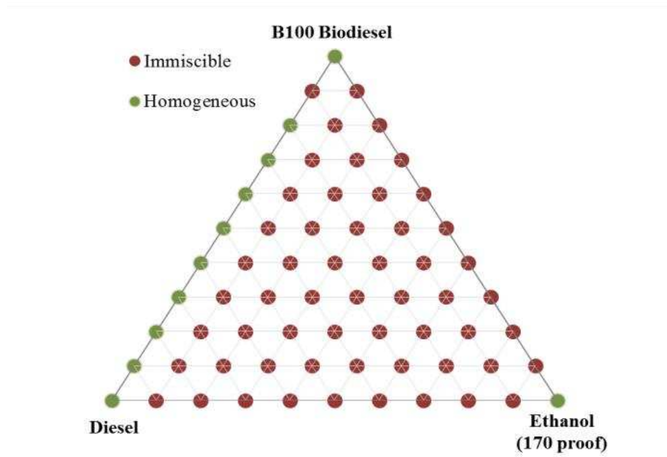

Figure 14. Ternary Phase Diagram (1.5°C)

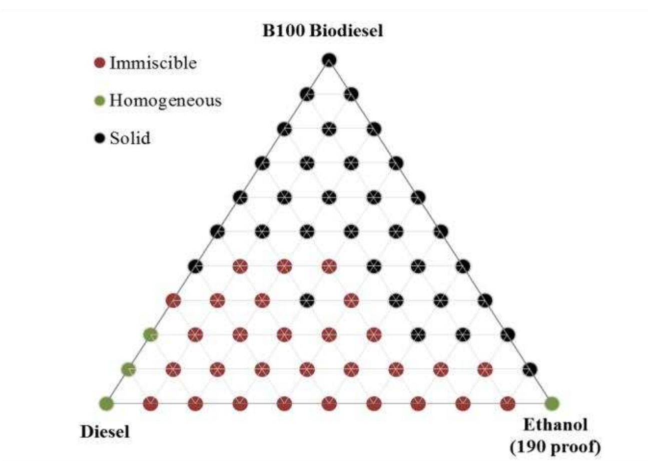

Figure 12. Ternary Phase Diagram (-17°C)

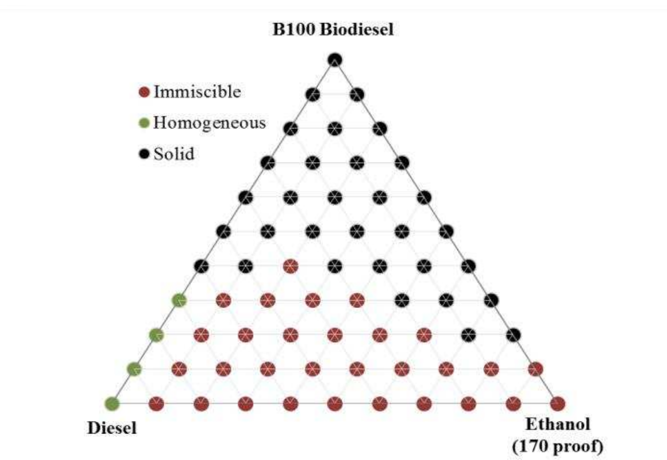

Figure 15. Ternary Phase Diagram (-17°C)

2.2 CETANE NUMBER

The ignition quality of a fuel operating in a compression ignition engine is defined by its cetane number. This is characterized by measuring ignition delay. Derived cetane numbers (DCN) were characterized at the CSU using a Waukesha Fuel Ignition Tester (FIT). The FIT operates in accordance with ASTM D7170 and utilizes a constant volume combustion chamber and sensors to indicate the difference between the start of fuel injection and the start of combustion. A derived cetane number is calculated from this time difference, which is the ignition delay.

Prior to performing measurements a calibration of the unit was performed. The calibration was conducted in accordance with the requirements of ASTM D7170. Results of the calibration are found in Table 1. Reference fuels used for the calibration were 99% anhydrous Heptane [$CH_3(CH_2)_5CH_3$] and 99% anhydrous Methylcyclohexane [$C_6H_{11}CH_3$].

Table 1. Waukesha FIT Calibration Results

Test Date	Test No.	Fuel	Actual ID (msec)	ARV or Expected Value
7/30/2015	1	Heptane	3.13	3.15 +/-0.04
7/30/2015	2	Heptane	3.17	3.15 +/-0.04
7/30/2015	3	Heptane	3.17	3.15 +/-0.04
	Avg		**3.16**	3.15 +/-0.02
7/30/2015	1	MCH	9.60	10.1 +/- 0.6
7/30/2015	2	MCH	9.61	10.1 +/- 0.6
	Avg		**9.61**	10.1 +/- 0.5

Following the calibration, samples of 100% diesel, 5% v/v 200 proof ethanol, 8% v/v 200 proof ethanol, 200 proof, 190 proof, 170 proof, and 150 proof ethanol were prepared for testing, again, according to ASTM D7170. Sample blends of diesel and ethanol were limited to only homogeneous blends of the two fuels. A baseline test of diesel fuel yielded an average DCN of 46.86, which measured above the minimum required cetane number (40) for diesel fuels in Colorado. [15] Table 2 summarizes the results of the DCN tests conducted. Values are averaged over a minimum of three tests. For all samples of pure ethanol the FIT failed to record a DCN due to ignition/injection failure. Ignition failure in this manner signifies that the test fuel has a cetane number below the operating limits of the device. This result is in agreement with the literature reviewed which predicted the cetane number of ethanol to be 5-15 [3]. Test samples containing 8% v/v ethanol had an average cetane number of 40.33, while samples containing 5% v/v ethanol had an average cetane value of 47.45. Unexpectedly, samples containing 5% v/v ethanol had a higher average cetane number than that of pure diesel.

Table 2. Average DCN results for select test fuels.

Test Fuel	Average DCN
Diesel	46.86
5% v/v% 200 proof ethanol	47.45
8% v/v% 200 proof ethanol	40.33
200 proof ethanol	---
190 proof ethanol	---
170 proof ethanol	---
150 proof ethanol	---

2.3 COLD FLOW PROPERTIES

Cloud point and cold filter plug point (CFPP) approximate the temperature at which a fuel may clog fuel filters or injectors (cold flow properties). These properties were measured using a Lawler DR4-14H Automated Cold Filter Plugging Point and Cloud Point Analyzer. This device fully conforms to ASTM D6371 and D2500 manual test methods. Due to operating limitations, test sample temperatures were limited to -26 and -22°C for cloud point and CFPP tests, respectively. Thus, some results show that the actual value of these properties is lower than the operating limits of the system. According to requirements set by the Colorado Department of Labor and Employment for diesel fuel cold flow property requirements start in October and continue through March. Since this fuel was purchased in July and is considered to be a ‘summer’ diesel blend so the results of these tests may not be indicative of a ‘winter’ diesel fuel which is sold between October and March. A baseline test of diesel fuel resulted in an average cloud point of -16°C and average CFPP of -13.4°C. Following the baseline test a blend of 5% v/v 200 proof ethanol was tested and showed an average cloud point and CFPP of greater than -26°and -15°C, respectively. In comparison to the diesel baseline values the addition of ethanol improved the cold flow properties; however, the discrepancy between the two results was unexpected. ASTM D975-15b states that cloud point is generally considered to be the most conservative cold flow property test, but clearly the CFPP test was more conservative in this test. Even with a discrepancy in values, this test shows that the cold flow properties of diesel can be improved with the addition of 200 proof ethanol. Finally, tests were conducted using 200, 190, 170, and 150 proof ethanol. In each test the measurement device was not able to calculate a result due to the operating limitations of the machine. The samples of 5% v/v ethanol in diesel and 100% ethanol behaved similarly up to the operating limit of the test device. Table 3 summarizes the cold flow property results for the fuels tested.

Table 3. Cold Flow Properties of Selected Fuels

Test Fuel	Cloud Point	CFPP
Diesel	-16°C	-13.4°C
5% v/v% 200 proof ethanol	< - 26°C	- 15°C
200 proof ethanol	< - 26°C	< - 22°C
190 proof ethanol	< - 26°C	< - 22°C
170 proof ethanol	< - 26°C	< - 22°C
150 proof ethanol	< - 26°C	< - 22°C

2.4. DENSITY AND VISCOSITY

Fuel viscosity and density play a significant role in the design of fuel injectors and other fuel delivery system components, and can impact the engine out emissions. Density and viscosity were measured using an Anton Paar SVM 3000/G2 digital density and viscometer. The machine fulfills all the requirements of ASTM standard D7042. Measurements were made using the M0-ASTM (precise) present measurement mode. This mode makes a single, precise measurement with automatic repetitions and is dedicated to use for measurements according to ASTM D7042. Figure 16 summarizes the average fuel viscosity and density for the selected fuels. Averages are the result of three consecutive, individual tests. As ethanol proof decreases both density and viscosity increase. This can be attributed to the increase volume percentage of water which has a higher density and viscosity than pure ethanol. Further, as ethanol was added to diesel both density and viscosity decreased which is attributed to the relatively lower density and viscosity of ethanol. Uncertainty associated with the density and viscosity measurements were calculated using the repeatability and reproducibility methods found in Section 15 of ASTM D7042.

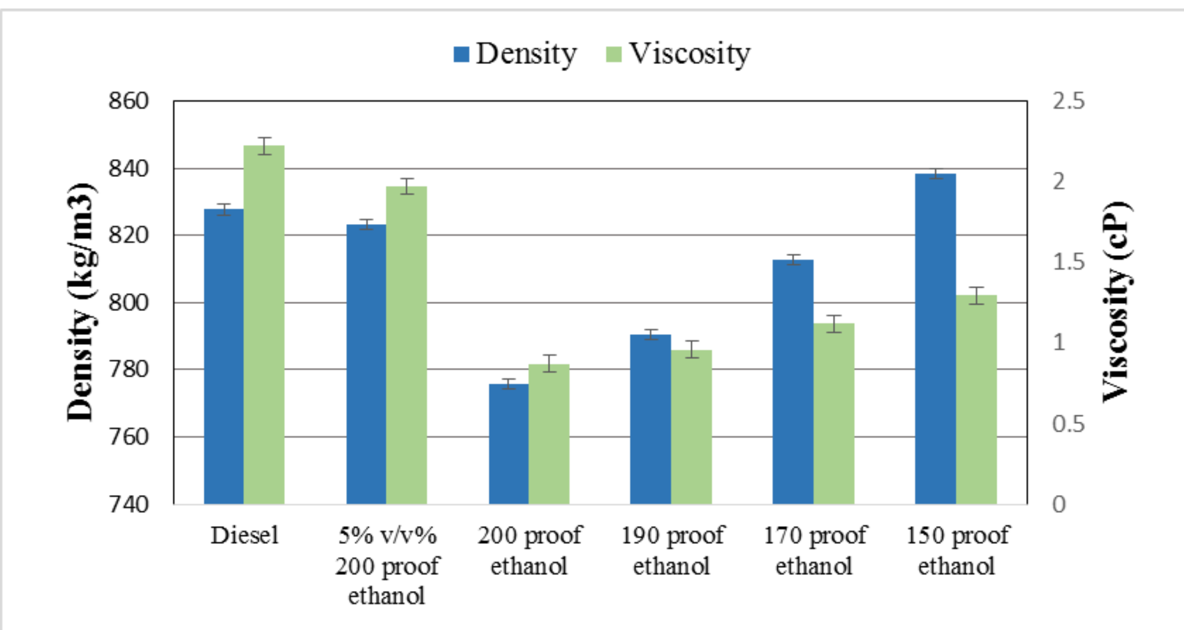

Figure 16. Density and Viscosity of Selected Fuels

2.5 HEATING VALUE

Higher heating value (HHV) of selected fuels was measured using an IKA C 200 Calorimeter system. Test fuels selected were diesel and 200, 190, 170, and 150 proof ethanol. Each fuel was tested three times with the average data presented in Figure 17. The HHV of 200 proof ethanol was approximately 70% of diesel fuel which was within 5% of the published ratio of diesel and ethanol heating values [16]. Decreasing proof level also lowered the HHV of the fuel. This is because ethanol is displaced by water, which is not combustible. Uncertainty bars in Figure 17 represent one standard deviation interval.

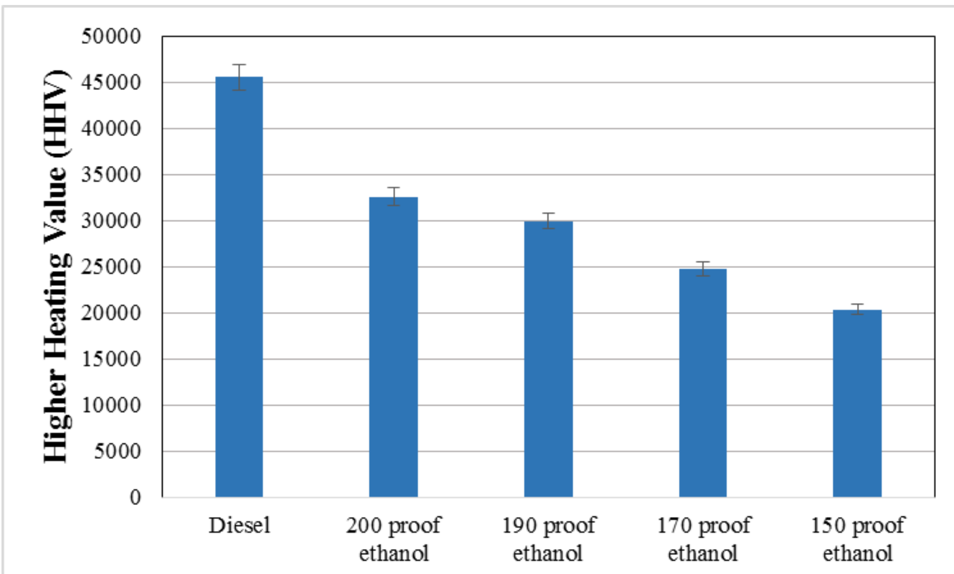

Figure 17. Higher Heating Value (HHV) of Selected Fuels

2.6 EXTENDED FUEL PROPERTY ANALYSIS

The lower right area of Figures 4-15 show fuels mixtures containing high volumetric percentages of ethanol. Figures 7 and 8 show that fuel blends of diesel fuel, biodiesel, and 200 proof ethanol containing up to 80% ethanol are homogeneous at 1.5°C. Fuel property analysis of four selected fuels containing high volumes of ethanol was performed at the Powerhouse Advanced Biofuels Combustion and

Characterization lab. The selected fuels shown in Figure 19 were first a mixture of 80% ethanol, 10% biodiesel, and 10% diesel, second, 70% ethanol, 20% biodiesel, and 10% diesel, third, 60% ethanol, 30% biodiesel, and 10% diesel, and finally 50% ethanol, 40% biodiesel, and 10% diesel fuel. As expected, fuel blends containing lower volumes of B100 biodiesel had both lower density and viscosity, and biodiesel was considerably more viscous and dense than 200 proof ethanol. In terms of density and viscosity each of the selected fuels may be suitable for a drop-in diesel fuel replacement due to the relative similarity of the measured values when compared to diesel fuel.

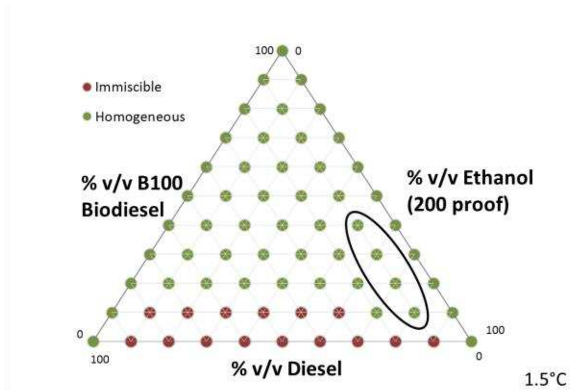

Figure 18. Homogeneous high ethanol content fuels selected for fuel property analysis

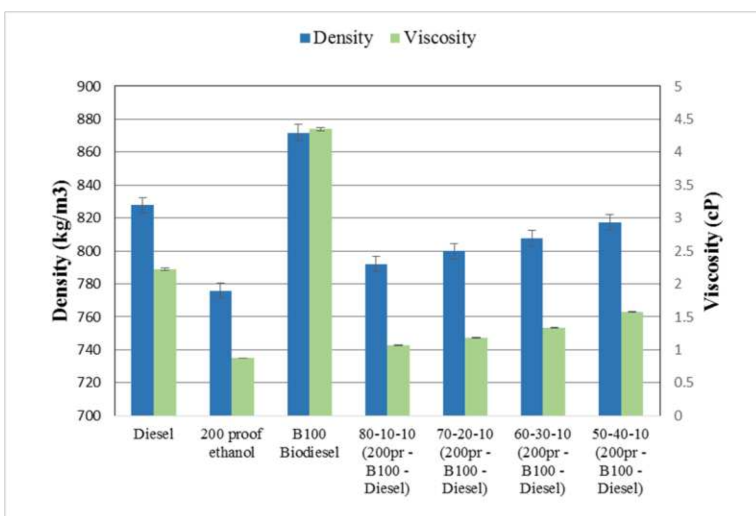

Figure 19. Density and Viscosity for selected high ethanol content fuel blends

The cold flow properties of these fuels were also examined with the results shown in Figure 20. When compared to the cold flow results of pure ethanol, mixtures containing high volumetric percentages of ethanol and low percentages of biodiesel exhibit cold flow characteristics closer to that of pure biodiesel. The four selected fuels blends could not be considered acceptable drop-in fuel replacements for diesel fuel during winter months. ASTM D975 appendix X5 shows the tenth percentile minimum ambient air temperatures for the United States. According to the standard the tenth percentile minimum is defined as the lowest ambient air temperature which will not go lower on average more than 10% of the time [20]. Table X5.1 in the standard shows tenth percentile minimums for each state in the U.S. In eastern Colorado the tenth percentile minimums for October through March are -2°C, -12°C, -14°C ,-19°C ,-15°C , and -12°C. Thus, the four blended fuels would not be suitable for use between November and March in eastern Colorado.

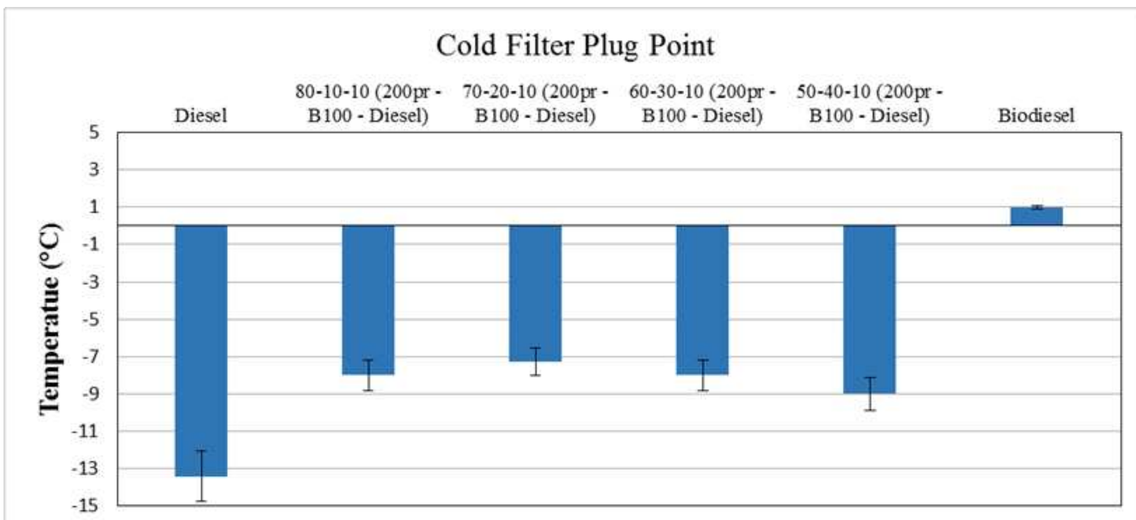

Figure 20. Cold Flow Properties for selected high ethanol content fuel blends

2.7 FUEL PROPERTY ANALYSIS SUMMARY

Fuel property tests conducted showed the following:

- Blends of ethanol and diesel fuel have a lower DCN value than diesel fuel alone.

- Cold flow properties of diesel fuel can be improved by blending 5% 200 proof ethanol with diesel fuel.
- Density and viscosity of 200 proof ethanol is lower than that of diesel; however, as ethanol proof level decreases both the density and viscosity increase.
- HHV of 200 proof ethanol is approximately 70% of diesel fuel, and decreases linearly with decreasing proof level.
- Decreasing blend temperature, increasing ethanol content, and decreasing ethanol proof degrade blend stability resulting in two phase, cloudy one phase, or solid blends.
- Two blends using 200 proof ethanol were able to achieve 80% ethanol substitution at 1.5°C: 80% 200 proof ethanol, 10% B100 biodiesel, 10% diesel and 80% 200 proof ethanol, 10% Span 80, 10% diesel.
- One blend using 190 proof ethanol was able to achieve 60% ethanol substitution at 25°C: 60% 190 proof ethanol, 30% B100 biodiesel, 10% diesel.
- Four fuels containing high volumes of ethanol were selected for further fuel property analysis. The results showed that these fuels may be suitable diesel fuel drop-in replacements during summer months of relatively warm climate areas such as Colorado.

2.8 IMPORTANCE OF THIS WORK

Given the previously stated benefits of intake air fumigation outlined in Chapter 1 and the fuel property analysis of ethanol-diesel blended fuels presented in Chapter 2 this combustion strategy was selected for an on-engine laboratory demonstration at the Engines & Energy Conversion Powerhouse Laboratory. The fuel property analysis and on-engine laboratory demonstration deviate and add to previously published literature in the following ways.

1) The on engine demonstration of ethanol intake air fumigation will be done on a Tier 4 Final diesel engine.

Published literature reviewed in Chapter 1 showed that intake air fumigation has been demonstrated in previous work. However, this this work has not been performed using a modern diesel engine equipped with the latest emissions mitigation and control technology. Modern diesel engines are designed to meet emissions standards that are an order of magnitude lower than previous standards, and are thus technologically very different from engines that are required to meet EPA Tier 2 and Tier 3 standards.

2) The ability of an aftertreatment system which incorporates an oxidation catalyst and selective catalytic reduction systems to reduce dual fuel emissions will be analyzed.

It has been found that ethanol intake air fumigation can lead to higher unburned hydrocarbon and carbon monoxide emissions when compared to diesel only operation. The increase of these emissions can lead to a net neutral effect of overall emissions and thus negate any improvements in NO_x and particulate matter emissions. This work will examine both engine out and post aftertreatment emissions to measure the ability of modern engine design and a oxidation catalyst to reduce unburned hydrocarbon and carbon monoxide emissions to an acceptable level.

3) The ability of B100 biodiesel to act as an emulsifier for mixtures of ethanol and biodiesel.

B100 biodiesel has been identified as an emulsifier for mixtures of 200 proof ethanol and diesel fuel. However, the ability of biodiesel to blend lower proofs of ethanol and diesel fuel, and its ability to stabilize blends at lower temperatures has not been demonstrated.

CHAPTER 3

ENGINE EXPERIEMENTAL METHODS

A new test cell was developed and constructed to facilitate on-engine dual fuel tests. The engine experiments seek to demonstrate the following

1) Show diesel-ethanol premixed combustion is a viable means by which to operate a compression ignition engine
2) Evaluate the impact of ethanol fuel blends and dual fuel on engine-out emissions and efficiency
3) Compare diesel-ethanol premixed combustion engine-out and post-catalyst emissions to diesel only combustion
4) Assess the effectiveness of a Tier 4 Final after treatment system on exhaust emissions
5) Determine the characteristics of both pre and post-after treatment particulate matter emissions
6) Examine the mechanisms that limit diesel substitution. Mechanisms that have been identified are engine knock, governor stability, and emissions requirements.
7) Test the impact of varying engine speed and load conditions on post-after treatment emissions.

3.1 ENGINE TEST PLAN

The objectives for an on-engine demonstration stated in the Chapter 3 introduction were used as a framework to develop the test plan for this study. Emphasis was placed on objectives 2-5 by taking emissions measurements both pre- and post- after treatment for test points whenever possible. Objective 6 was met by increasing ethanol flow rate until one of the limiting factors was reached, and recording the applicable test data. Engine operation points were selected from ISO 8178 standard for exhaust emission measurement for non-road engines. The ISO 8178-C1/C2 test cycles are 8 mode cycle maps. Weighting factors for the 8 different engine operating points are assigned to calculate a single emission value. Three operating points were tested during this study which were C1-3, C2-4, and C1-7. These points refer to rated speed-50% torque, rated speed-25% torque, and intermediate speed-75% torque, respectively. A final consideration was the type of ethanol fuel to be used as a dual fuel. The first dual fuel selected was 200 proof ethanol. The infrastructure to produce and distribute this fuel is well established in the Midwestern states of the U.S. To date there are approximately 2800 fuel stations in the U.S. that offer E85 fuel. [19] The technology and storage capabilities of these sites would be crucial to any market implementation of a 200 proof ethanol diesel-ethanol dual fuel technology. The second dual fuel selected was 190 proof ethanol. This fuel is lucrative because of the reduced production cost as compared to 200 proof ethanol. The final dehydration step in the ethanol production process is energy intensive, and if this step could be excluded the production cost of ethanol could be reduced. This theory was confirmed after discussions and interviews with the plant manager and general manager of Front Range Energy, an ethanol production facility located in Windsor, Colorado. Finally, E85 fuel was selected as a test dual fuel. The infrastructure for this ethanol premixed combustion strategy is already in place at fuel stations around the U.S. Currently, according to ASTM 5798, E85 fuel is allowed to have an ethanol content between 51% and 83%. E85 fuel used for this engine test was mixed to have a composition of 85% ethanol and 15% E0 gasoline.

Table 4 contains the list of tests completed in this study. It includes the three ISO 8178 test points, three selected dual fuels, two emissions sampling locations which are pre and post after treatment system, and two diesel substitution points.

3.2 ENGINE CONFIGURATION

The engine selected for this diesel-ethanol dual fuel demonstration was a 2015 Cummins QSB 6.7L CM2350 B105 (S/N: 73915597) heavy duty diesel engine. This engine was paired with Cummins Tier 4

Table 4. Engine test points

Test No.	Fueling Strategy	Dual Fuel	Engine Speed	Engine Torque	Emissions Sampling Location	Diesel Substition
1	Diesel Only	---	Intermediate	75%	Pre-Aftertreatment	---
2	Dual Fuel	200 proof	Intermediate	75%	Pre-Aftertreatment	12%
3	Dual Fuel	200 proof	Intermediate	75%	Pre-Aftertreatment	Maximum
4	Dual Fuel	200 proof	Intermediate	75%	Pre-Aftertreatment	Maximum
5	Dual Fuel	200 proof	Intermediate	75%	Post-Aftertreatment	12%
7	Dual Fuel	200 proof	Intermediate	75%	Post-Aftertreatment	Maximum
11	Diesel Only	---	Intermediate	75%	Pre-Aftertreatment	---
12	Dual Fuel	190 proof	Intermediate	75%	Pre-Aftertreatment	12%
14	Dual Fuel	190 proof	Intermediate	75%	Pre-Aftertreatment	Maximum
15	Dual Fuel	200 proof	Rated	50%	Post-Aftertreatment	Maximum
16	Dual Fuel	200 proof	Rated	25%	Post-Aftertreatment	Maximum
17	Dual Fuel	190 proof	Intermediate	75%	Post-Aftertreatment	12%
19	Dual Fuel	190 proof	Intermediate	75%	Post-Aftertreatment	Maximum
20	Dual Fuel	190 proof	Rated	50%	Post-Aftertreatment	Maximum
21	Dual Fuel	190 proof	Rated	25%	Post-Aftertreatment	Maximum
22	Dual Fuel	E85	Intermediate	75%	Post-Aftertreatment	12%
23	Dual Fuel	E85	Intermediate	75%	Post-Aftertreatment	Maximum
24	Dual Fuel	E85	Rated	50%	Post-Aftertreatment	Maximum
25	Dual Fuel	E85	Rated	25%	Post-Aftertreatment	Maximum
26	Diesel Only	---	Intermediate	75%	Post-Aftertreatment	---
27	Diesel Only	---	Intermediate	75%	Pre-Aftertreatment	---
28	Dual Fuel	E85	Intermediate	75%	Pre-Aftertreatment	12%
29	Dual Fuel	E85	Intermediate	75%	Pre-Aftertreatment	Maximum
30	Diesel Only	---	Rated	25%	Pre-Aftertreatment	---
31	Diesel Only	---	Rated	50%	Pre-Aftertreatment	---
32	Diesel Only	---	Intermediate	75%	Pre-Aftertreatment	---

Final emissions technology which includes diesel oxidation catalyst (DOC) and selective catalytic reduction (SCR) systems. According to Cummins literature the QSB 6.7L is one of the most popular and versatile engines ever built. It is used in various types of construction equipment such as the Grove RT890E rough terrain crane and the Hyster H550-700HD/S high capacity forklift truck. It is also used in agriculture applications such as the Miller Nitro 5300 sprayer and the Vermeer BC2100XL Tier 4 Final brush chipper. Figures 22 and 23 show front and rear views of the engine prior to its installation into the test cell. The engine features a variable geometry turbocharger, an exhaust gas recirculation system, a direct injection fuel system, and a common rail high pressure fuel rail. Using the engine serial number, all engine specifications including an owner’s manual, service manual, and general wiring diagram can be found at the Cummins Quickserve website (https://quickserve.cummins.com/info/index.html). Detailed

Table 5. Cummins 6.7L QSB Tier 4 Final Engine Specifications

Cummins 6.7L QSB Tier 4 Final	
Maximum Power @ 2500 RPM	224 kW
Maximum Torque @ 1800 RPM	1030 Nm
Cylinders	6
Aspiration	Turbocharged
Bore	107 mm
Stroke	124 mm
Aftertreatment	DOC & SCR
Fuel System	HPDI

system specific wiring diagrams can be found in Appendix A. Table 5 contains information pertinent to engine operation.

Cummins Calterm 3 Bulldog v3.16.0.009 engine control software was used to monitor engine control unit (ECU) parameters during tests. This software was installed on the Powerhouse PEC-EECL-1 laptop, and an image of the license configuration and calibration names and locations can be found in Appendix A. The current license file is valid only until June 7, 2017 after which a new license file will need to be requested from Cummins to utilize the Calterm software for this engine. The software was linked to the engine PCAN network via a Peak Systems PCAN-USB IPEH-002022 adapter. While the ECU is running Calterm allows a user to view and log data parameters such as engine speed, net torque, exhaust temperature, and injection timing. A complete list of Calterm parameters logged during engine tests can be found in Appendix A. The majority of this list contains parameters that can be used for troubleshooting and diagnostics. These parameters were found to be important to monitor and continuously log during engine tests.

The engine ECU receives and sends information continuously to monitor and control various operational parameters including diesel injection timing, urea fluid flow, rate of diesel fuel injection, and sensor power. The basic inputs and outputs of the engine ECU are shown in Figure 21. Engine speed is a direct input from the operator, and in the Calterm software is given the parameter name accelerator position. This is analogous to the accelerator pedal depressed to increase the speed of a vehicle. Torque is applied to the engine via a dynamometer while pressure and temperature are monitored and used to optimize outputs such as fuel flow and timing. The final basic input to the ECU is NO_x sensor feedback. The engine is equipped with these sensors before and after the aftertreatment system, and provides real time measurements of NO_x. These input parameters collectively map the output parameters shown in Figure 21. VGT vane angle is an output used to control turbocharger speed and subsequently charge pressure, and EGR Valve percentage controls the amount of exhaust gas recirculated back into the intake manifold.

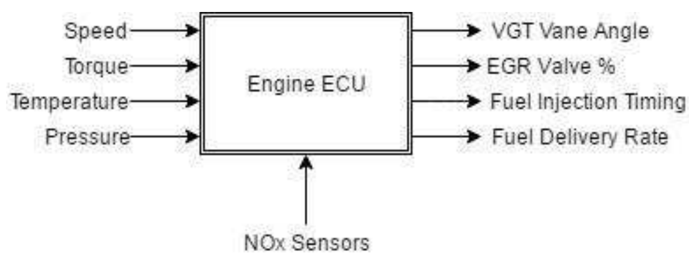

Figure 21. Engine ECU Block Diagram

Figure 22. 2015 Cummins 6.7L Tier 4 Final engine donated by Cummins to be used for diesel-ethanol premixed combustion study.

Figure 23. 2015 Cummins 6.7L engine viewed from the rear

3.3 DUAL FUEL SYSTEM

A Snow Performance MPG-MAX Fuel Injection System was selected to inject ethanol based fuels into the engine intake manifold air stream. This system can be purchased commercially from Snow Performance and was originally designed to inject blends of water and methanol into an engine intake manifold to achieve better fuel economy and higher engine power. It includes a fuel injector, solenoid valve, fuel pump, safe injection controller, exhaust temperature probe, charge air sample tube, and controller. The system is shown Figures 24 and 25 mounted onto the engine with the fuel injectors positioned between the intercooler and intake manifold.

The system controller has a display screen that has three display modes and seven control screens. The first display mode is a read only mode. In this setting the boost pressure and exhaust gas temperature will be displayed, but there is no display of injection percentage. The second display mode is called

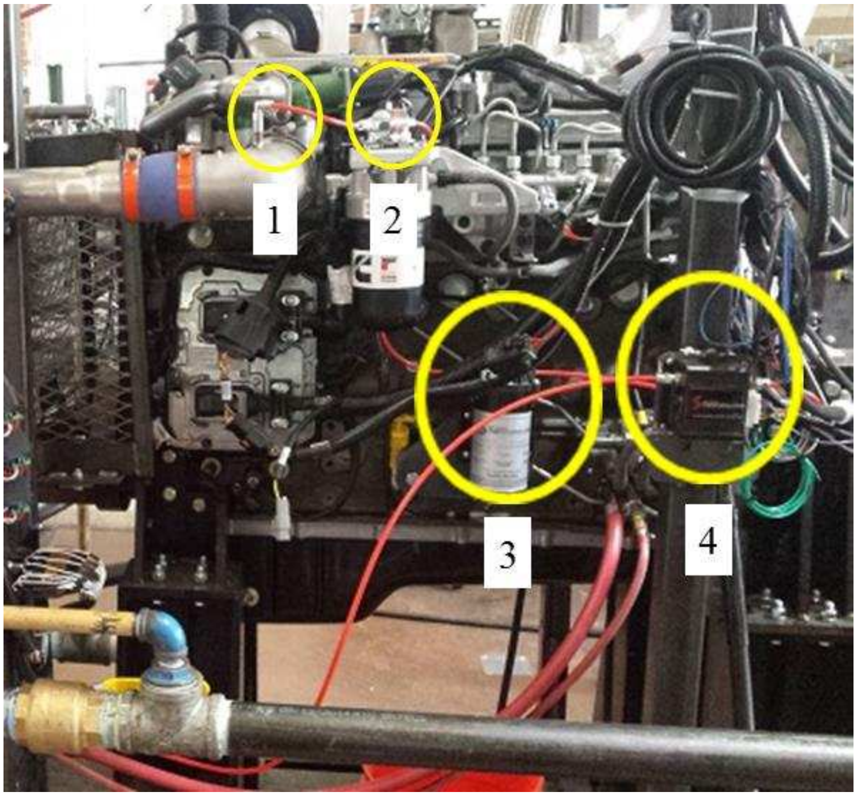

Figure 24. Ethanol Injection System: (1) Fuel Injector (2) Solenoid Valve (3) Fuel Pump (4) Safe Injection Controller

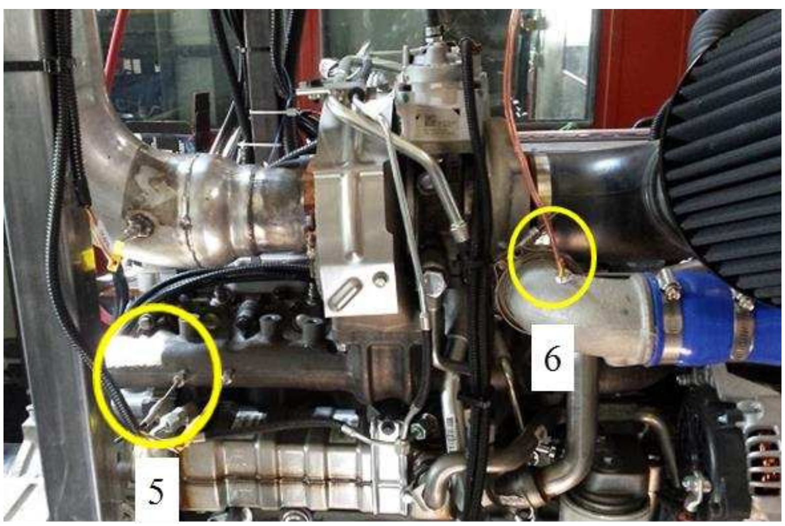

Figure 25. Ethanol Injection System: (5) Exhaust Temperature Probe (6) Charge air sample tube

‘MPG’. In this setting fuel injection is controlled by boost pressure only. The user is able to program the device to inject fuel at any desired boost pressure though the owner’s manual recommends that the start of injection be set just above the vehicle cruising boost pressure. The final display mode is called ‘Tow Mode’. In this setting the controller will measure exhaust gas temperature and boost pressure to calculate a recommended injection rate. The required user input is a range of boost pressure in which an engine will operate. The ‘MPG’ mode was used for testing in this project. The charge air sample line was connected to a controlled pressure source such that the amount of ethanol injected could be adjusted manually. Six separate fuel injectors are available to span a fuel injection range of 0 – 625 mL/min, and because the maximum allowable dual fuel injection was not known, all six injectors were installed on the engine in order to span the entire range of the system. Figure 26 shows the location of the injectors installed on the engine air intake system.

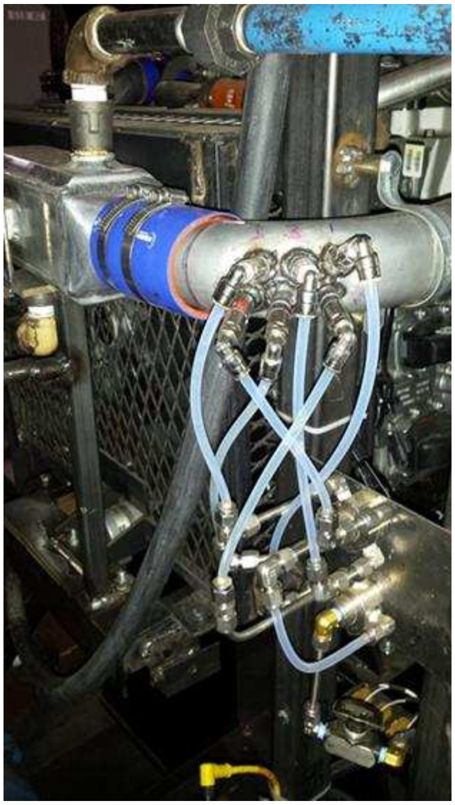

Figure 26. Fuel injectors installed between the engine intercooler and intake manifold.

Table 6. Published injection rates for dual fuel kit injectors

Nozzle Number	Max Nozzle Flow (mL/min)	Nozzle Number	Max Nozzle Flow (mL/min)
1	60	4	225
2	100	5	375
3	175	6	625

3.3.1. INJECTOR FLOW MAPPING

Actual injection rates of the fuel injector nozzles may vary when fuel is injected into a high pressure flow such as a diesel engine intake manifold. For this reason injector flow was measured gravimetrically while fuel was injected into a pressurized chamber. The chamber pressure corresponded to the engine boost pressure at selected engine operation points of rated speed-50% torque, rated speed-25% torque, and intermediate speed-75% torque. Figures 27-29 represent the individual injector flow rates as a function of a digital 'injection %' reading displayed on the injection system controller.

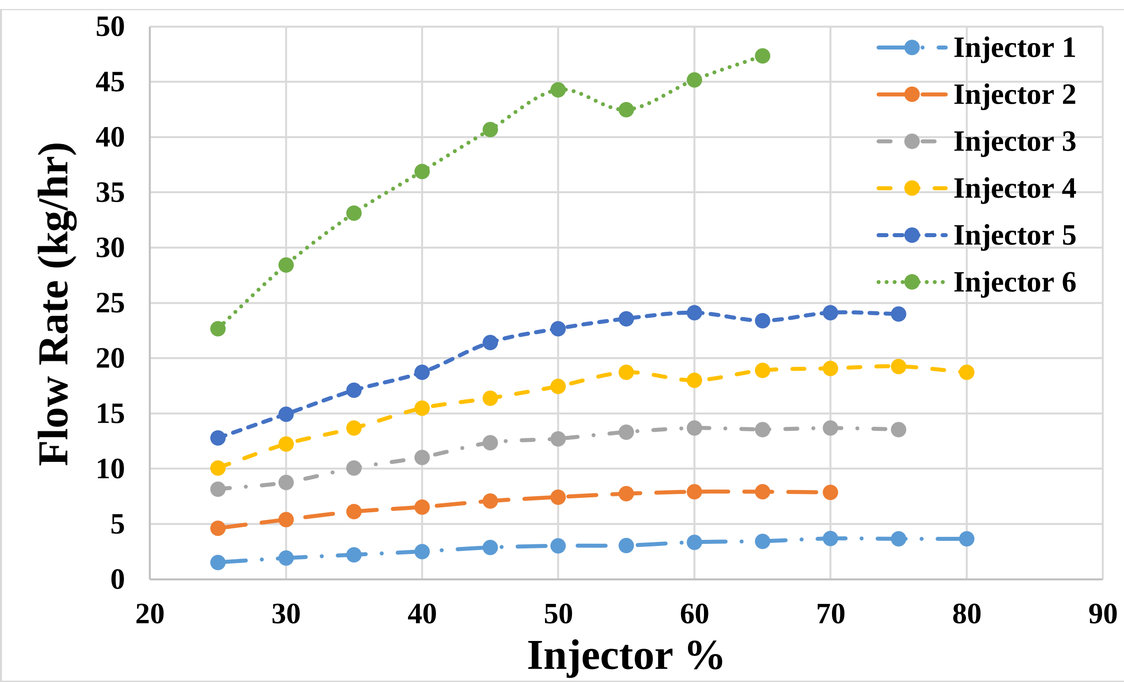

Figure 27. Dual fuel injector mass flow rates while injecting into ambient pressure of 35 psia. Analogous to intake manifold pressure at engine speed of 1800 rpm and 75% torque.

3.4. MEASUREMENT DEVICES

3.4.1. EXHAUST GAS ANALYZERS

Engine exhaust gas species were analyzed using a Rosemount 5-gas analyzer rack with Siemens instrumentation. Species determined using this instrumentation were carbon monoxide (CO), carbon dioxide (CO_2), total hydrocarbons (THC), oxygen (O_2), and oxides of nitrogen (NO_x). Additional emissions including methane, ethane, formaldehyde, and ammonia were measured using a Fourier Transform InfraRed Spectrometer. Detailed information about the gaseous emission sampling instruments can be found by referencing Davis [22]. A complete list of all gas species emissions measured with these two instruments is compiled in Table 7.

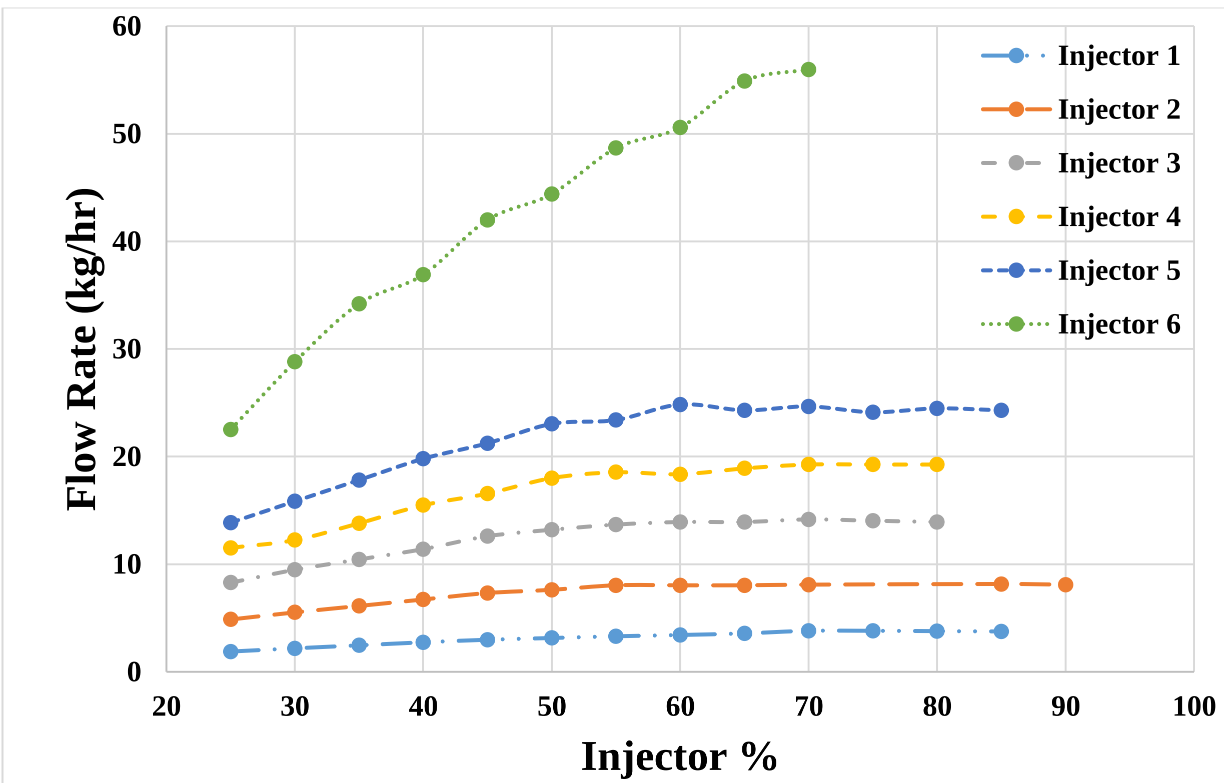

Figure 28. Dual fuel injector mass flow rates while injecting into ambient pressure of 30 psia. Analogous to intake manifold pressure at engine speed of 2500 rpm and 25% torque.

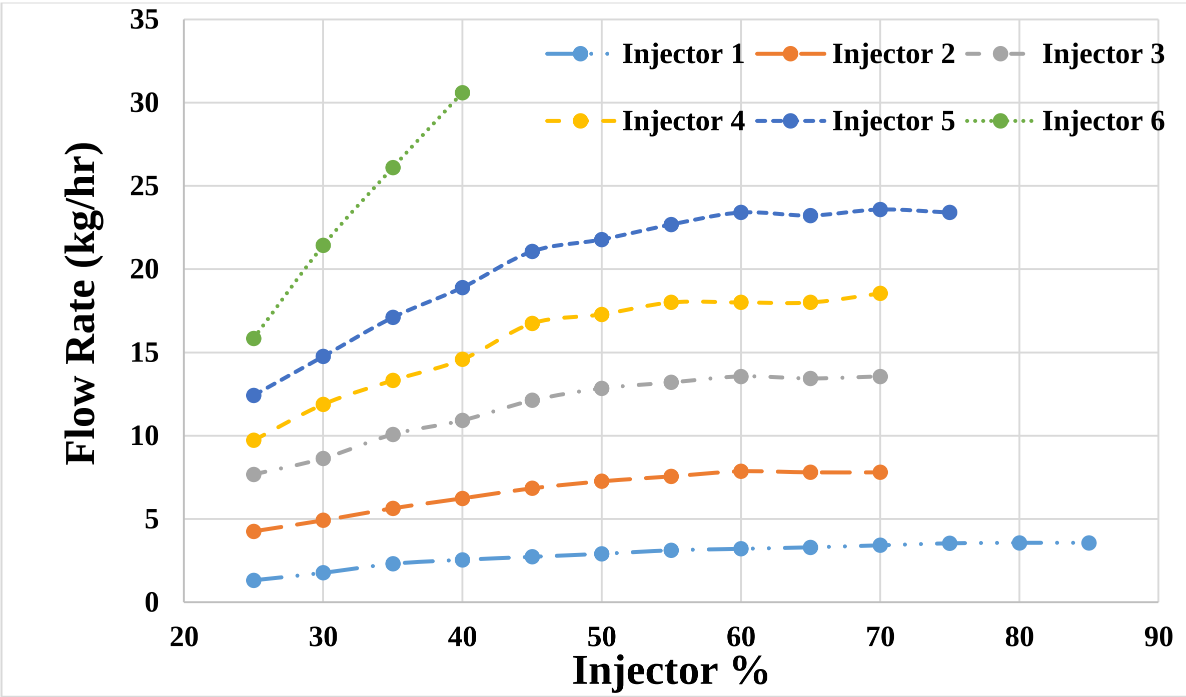

Figure 29. Dual fuel injector mass flow rates while injecting into ambient pressure of 38 psia. Analogous to intake manifold pressure at engine speed of 2500 rpm and 50% torque.

Table 7. Gas emissions measurements

FTIR Instrument	5-Gas Rack
Carbon Monoxide high	THC (ppm)
Carbon Dioxide	O2 (%)
Nitric oxide	NOx (ppm)
Nitrogen dioxide	CO2 (%)
Methane	CO (ppm)
Ethylene	
Ethane	
Propylene	
Formaldehyde	
Water	
Propane	
Hydrogen cyanide	
Ammonia	
Carbon Monoxide low	
Ethanol	
Methanol	

3.4.2. PARTICULATE MATTER

A mini dilution tunnel was used to measure particulate matter in engine exhaust. A small portion of the exhaust flowed through a heated sample line to the dilution tunnel, mixed with ambient air, and flowed into a residence chamber to simulate particulate mixing. While in this chamber the temperature and pressure were measured. A portion of this this flow was taken from the residence chamber and passed through a cyclone where all particulates larger than 10 μm were removed. Downstream of this cycle, two sample collection cartridges were used to collect particulate matter. The first cartridge contained only a quartz filter which absorbs and collects all particulate matter including gaseous and semi-volatile particles. The second cartridge included a teflon and quartz filter. The Teflon filter was placed up stream of the quartz filter. Elemental carbon deposits on the surface of this filter while semi-volatile and gaseous particulates that pass through this filter are collected on the downstream quartz filter. Prior to use, Teflon filters were weighed using a high resolution balance capable of making measurements accurate to 1 μm. After being exposed to exhaust emissions the filters are weighed again, and the difference in post and pre weights results in the total mass of particulate matter produced by the engine as a function of engine operating load and collection time.

Quartz filter analysis was conducted using a Sunset Laboratory Model 5L OC-EC Aerosol Analyzer. This analyzer is the basis for National Institute for Occupational Safety and Health (NIOSH) Method 5040 [23]. After particulate matter was collected the quartz filters were immediately stored at -40 °C to prevent any volatilization of the particles absorbed on the filter. Samples were then prepared according NIOSH 5040 Method and analyzed. While being analyzed deposits of carbon are 'thermally desorbed from the filter in an inert helium atmosphere followed by an oxidizing atmosphere using carefully controlled heating ramps.' [24] A flame ionization detector (FID) is used to measure the concentration of carbon released at each ramp temperature.

3.4.3. COMBUSTION ANALYSIS

High speed combustion data was collected on four of six engine cylinders via in-cylinder piezoelectric pressure transducers. Five cylinder heads on the Cummins QSB engine were machined to hold the transducers. Cylinders two, three, five, and six were selected to collected combustion data during tests. Cummins recommended that the cylinder one head not be machined for a pressure transducer due the limited options of transducer placement on the cylinder head. An additional pressure transducer could have been placed in cylinder four, but was not utilized due to its relatively inaccessible location underneath the turbocharger. Figure 30 shows the four pressure transducers installed into the engine cylinder heads. The black tubes are coolant supply and return lines, and metallic colored wires are the transducer signal wires. Table 8 lists individual pressure transducer sensitivity and the cylinder in which each was installed. The sensitivity range used for this study was the 0-250 [pC / bar].

The pressure transducers were connected to charge amplifiers during engine tests and the signals were processed on a National Instruments PXI-1002. A high resolution encoder was connected to the crankshaft of the engine to provide crankshaft position and instantaneous engine speed. In addition to cylinder pressure other combustion characteristics such as indicated mean effective pressure (IMEP), heat release, burn mass fraction, and knock analysis were also analyzed for each engine test point.

Knock analysis was done by a fast Fourier Transform (FFT) method. The software for this analysis was developed during previous work at the CSU Powerhouse Laboratory by Wise [21] and requires that the user select either an ‘events’ or ‘integration’ method for the knock analysis. The integration method was used for the data collected during these engine tests and the cycle count window was set to 50 cycles.

Figure 30. In-cylinder pressure transducers on the Cummins 6.7 L QSB engine. In the foreground are cylinders six and five respectively.

Table 8. Pressure transducer specifications and cylinder location

Kistler Type 6067C Pressure Transducer				
S/N	4603482	4603484	4603486	4603485
Calibrated Range / Sensitivity [bar] / [pC / bar]	0-250 / 26.95	0-250 / 26.92	0-250 / 27.05	0-250 / 27.06
	0-150 / 26.88	0-150 / 26.85	0-150 / 26.97	0-150 / 26.90
	0-100 / 26.89	0-100 / 26.85	0-100 / 26.97	0-100 / 26.85
QSB 6.7L Cylinder	2	3	5	6
Charge Amp Cylinder	2	3	4	1

CHAPTER 4
COMBUSTION ANALYSIS

4.1 OVERVIEW

High-speed combustion data was gathered for each engine operating point conducted during this study. This data was used to calculate cylinder combustion traces, heat release rates, fuel mass fraction burned, and knock analysis data. Engine operating parameters such as turbo speed and diesel fuel injection timing that affect combustion were not controlled during these tests. However, these parameters will be noted when comparing combustion results from different dual fuels and diesel only operation.

4.2 PRESSURE TRACES

Diesel fuel combustion traces for cylinder 6 of the Cummins 6.7 L QSB engine are shown in Figure 31. The main fuel injection event for each load case can be identified by the colored dot on each pressure trace. The complete fuel injection event for this engine includes a pilot injection at varying crank angle, but only the main start of injection (mSOI) was logged during engine testing. Approximate motored pressures for the three load cases were superimposed onto the figure to show the deviation of combustion and motored pressures. These traces were created using Equation 1 given the ratio of specific heats equal to 1.35, initial pressure found from the charge pressure parameter in Calterm, and engine geometry from the Cummins Quickserve website.

$$P_n = P_{n-1} + \Delta\Theta \left(-\gamma \frac{P_n}{V} \frac{dV}{d\Theta}\right) \tag{1}$$

The maximum pressure rise rate (PRR) recorded for the 25%, 50%, and 75% torque traces was 27.8 kPa/CA, -52.1 kPa/CA, and 256 kPa/CA respectively. These values will be used as baseline diesel only combustion PRR, and compared to dual fuel PRR.

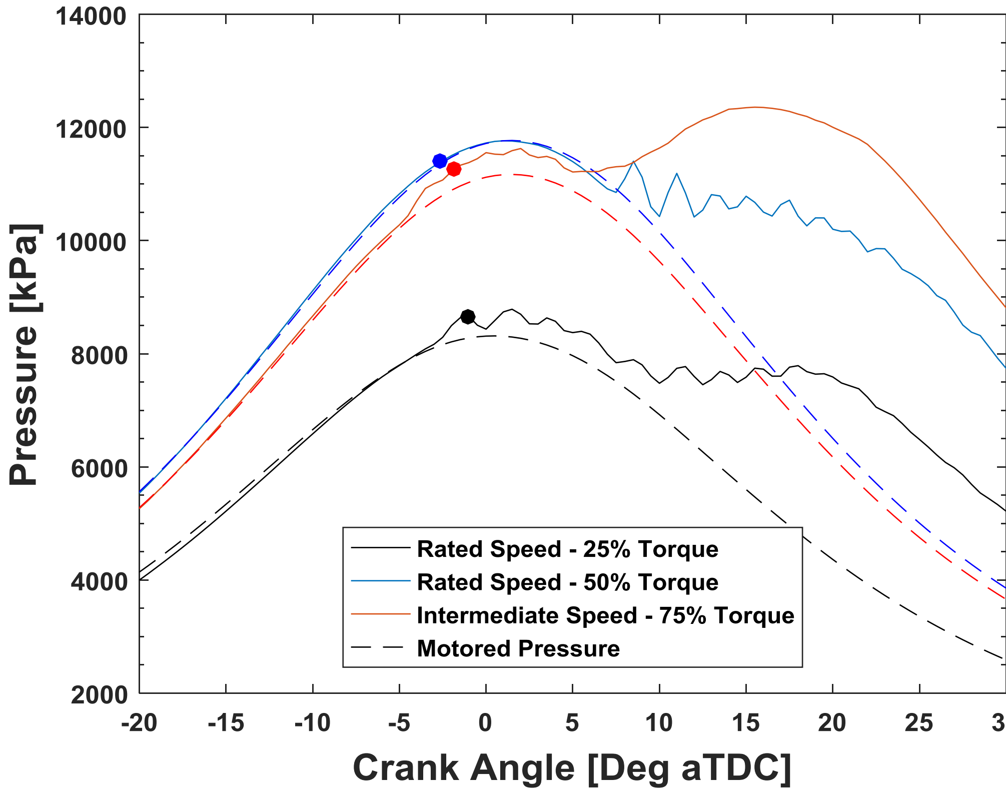

Figure 31. Diesel fuel combustion traces for the three engine test points selected. Traces were taken from engine cylinder 6. Main SOI for the 25%, 50%, and 75% torque traces represented by the colored, heavy circles are 1 °BTDC, 2.7 °BTDC, and 1.9 °BTDC, respectively.

It was decided that the first test point at intermediate speed and 75% torque would be a 12% diesel fuel substitution point. This diesel fuel substitution would be consistent across all dual fuel tests to provide a common comparison point. As shown in Figure 32 all dual fuel tests showed a reduction in intake manifold pressure due to change in the variable geometry turbo (VGT) vane position, and as a result turbo speed. The average reduction in intake manifold pressure for all dual fuel tests in Figure 32 was 3%.

For all dual fuel pressure traces, a sharp deviation from the cylinder motored pressure occurs prior to the recorded mSOI. The timing of pilot diesel fuel injections was not recorded so is not possible to determine if this start of combustion is due to a pilot injection of diesel fuel or compression ignition of the

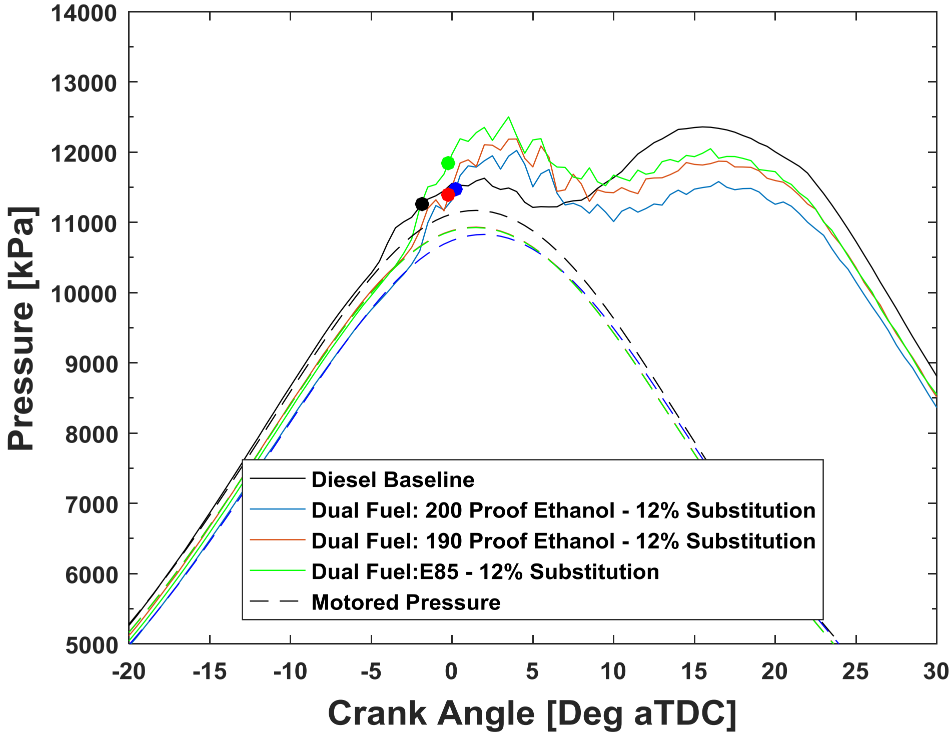

Figure 32. Combustion traces for cylinder 6 at 1800 rpm and 75% torque. Diesel substitution for all dual fuel traces was approximately 12%. Main SOI for the diesel baseline, 200 proof dual fuel, 190 proof dual fuel, and E85 dual fuel shown by the heavy, colored circles were 1.9 °BTDC, -0.2 °BTDC, 0.2 °BTDC, and 0.2 °BTDC, respectively. Main SOI was controlled by the ECU during tests.

pre-mixed dual fuel and air. During the initial pressure rise of ethanol premixed combustion, a distinct drop in pressure is observed. This pressure drop is further pronounced in Figure 33, and a correlation can be made between this drop in pressure and the main diesel fuel SOI. Pressure rise rates during initial ethanol premixed combustion of 200 proof ethanol, 190 proof ethanol, and E85 were 490 kPa/CA, 413 kPa/CA, and 631 kPa/CA respectively.

Maximum diesel substitution limits were found by increasing dual fuel injection until engine knock, speed instability, or excessive emission were observed. At intermediate speed and 75% torque the limiting factor for diesel substitution was engine knock. After the engine knock limit was determined the dual fuel injection was lowered and test data was taken. For all dual fuels the maximum diesel substitution at 1800 rpm and 75% torque was approximately 25%. The data in Figure 33 represents the maximum allowable diesel substitution before engine knock occurred. Similar, yet more pronounced ethanol premixed combustion is observed between negative five and five °ATDC. This combustion can conclusively be identified as ethanol premixed combustion by comparing the maximum PRR of these traces to that of diesel fuel (256 kPa/CA) where the maximum PRRs of 200 proof, 190 proof, and E85 dual fuel traces were 1021 kPa/CA, 936 kPa/CA, and 767 kPa/CA, respectively. Dual fuel tests experienced a 16% reduction in intake manifold pressure again due to the change in VGT vane angle. The audible knock trace for 200 proof ethanol is also included in Figure 33, and has a PRR of 1314 kPa/CA. The noise frequency between zero and five °ATDC in dual fuel traces can be identified as inaudible, incipient knock, and will be further discussed later in this chapter.

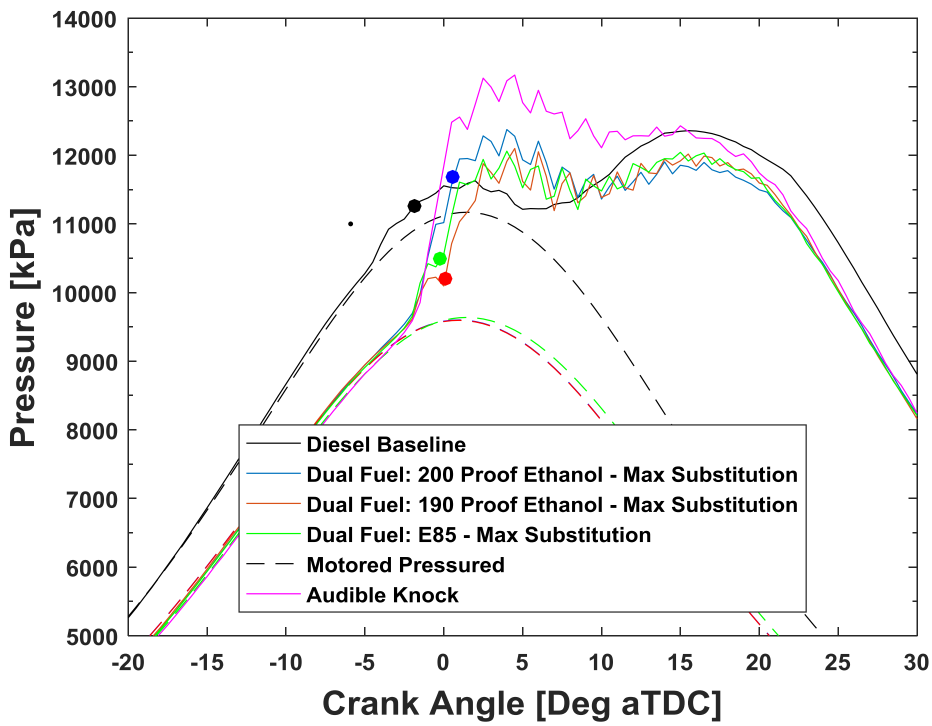

Figure 33. Combustion traces for cylinder 6 at 1800 rpm and 75% torque. Diesel substitution for all dual fuel traces was approximately 25%. Main SOI for the diesel baseline, 200 proof dual fuel, 190 proof dual fuel, and E85 dual fuel shown by the heavy, colored circles were 1.9 °BTDC, -0.6 °BTDC, -0.1 °BTDC, and 0.2 °BTDC, respectively.

Figure 34 shows combustion traces for cylinder six while the engine was operating at rated speed – 50% torque. Maximum diesel substitution rates at this engine load were limited by engine knock similar to the 1800 rpm-75% torque test point. However, due to lower engine load, the achievable substitution rates were much higher. The maximum diesel substitution found was to be 43% using 200 proof ethanol as the dual fuel. Using E85 and 190 proof ethanol as dual fuels resulted in slightly lower diesel substitution rates of 39% and 37% respectively. Injection delay in ethanol premixed combustion can be observed at this test point. In contrast to the 1800 rpm-75% torque test, the combustion event occurs almost exclusively after top dead center which results in a more efficient combustion process. The knock trace for 200 proof ethanol has a PRR of 1030 kPa/CA and is included in Figure 34.

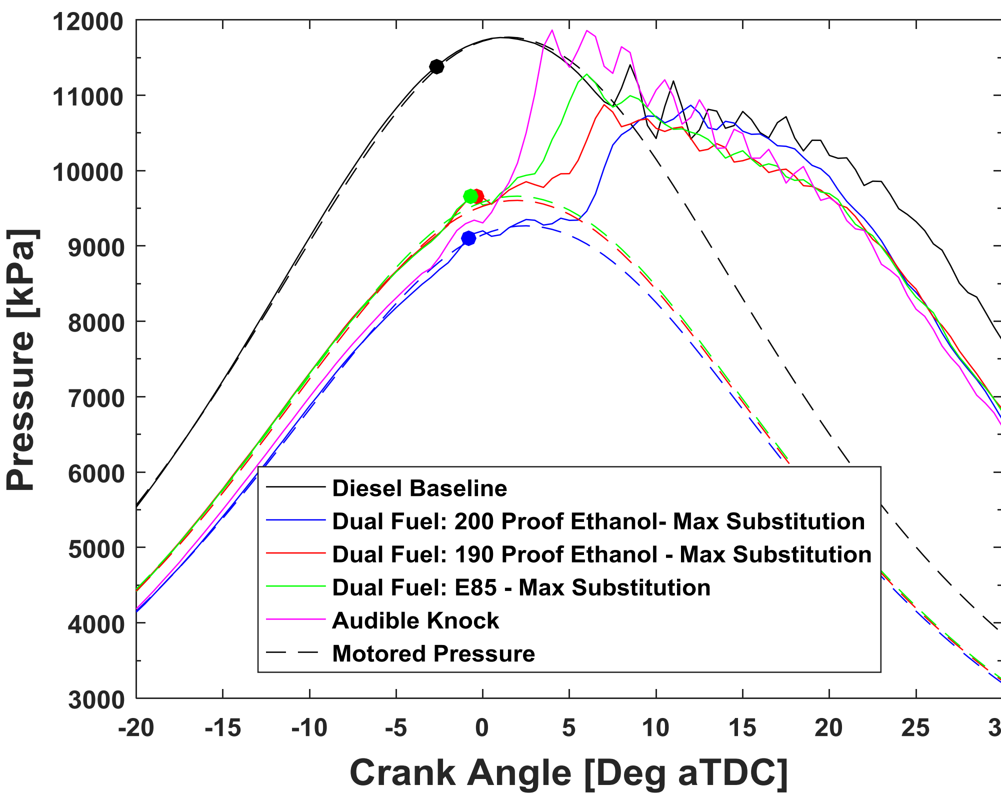

Figure 34. Combustion traces for cylinder 6 at 2500 rpm and 50% torque. Maximum diesel substitution levels for 200 proof, 190 proof, and E85 dual fuel tests were 43%, 39%, and 37%, respectively. Main diesel SOI shown by the colored, heavy circles were 0.8 °BTDC, 0.4 °BTDC, and 0.7 °BTDC for the tested dual fuels.

Diesel fuel substitution for the rated speed-25% torque test was limited by exhaust emission requirements, and will be covered in Chapter 4. The dual fuel traces shown in Figure 35 do not exhibit a clear ethanol premixed combustion event. This could be due to large amounts of unburned hydrocarbons that are not contributing to the combustion process.

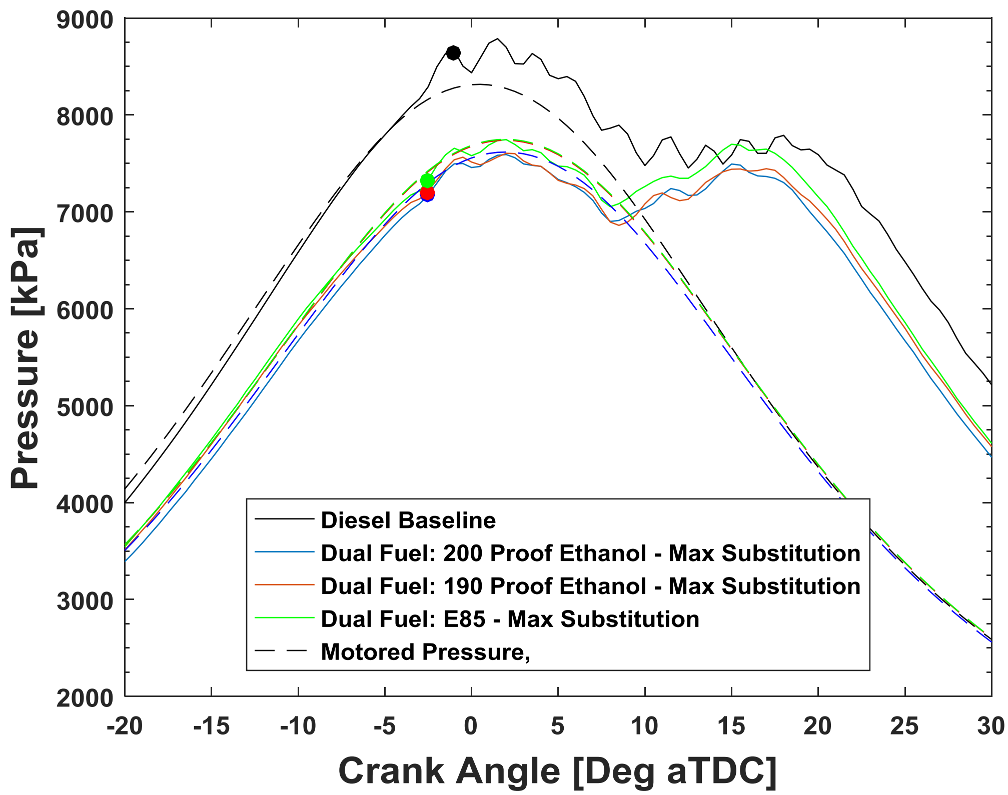

Figure 35. Combustion traces for cylinder 6 at 2500 rpm and 25% torque. Maximum diesel substitution levels for 200 proof, 190 proof, and E85 dual fuel tests were 26%, 24%,, and 25%, respectively. Main diesel SOI shown by the heavy, colored circles was 2.5 °BTDC for all dual fuel test points and 1°BTDC for the diesel baseline test point.

4.3 HEAT RELEASE & MASS FRACTION BURNED

Figures 36 and 37 depict net heat release rate (NHRR) and mass fraction burned (MFB) traces while the engine was operating at 1800 rpm and 75% torque for a 12% diesel substitution and 25% diesel substitution respectively. All dual fuel traces include a significant heat release event prior to the diesel

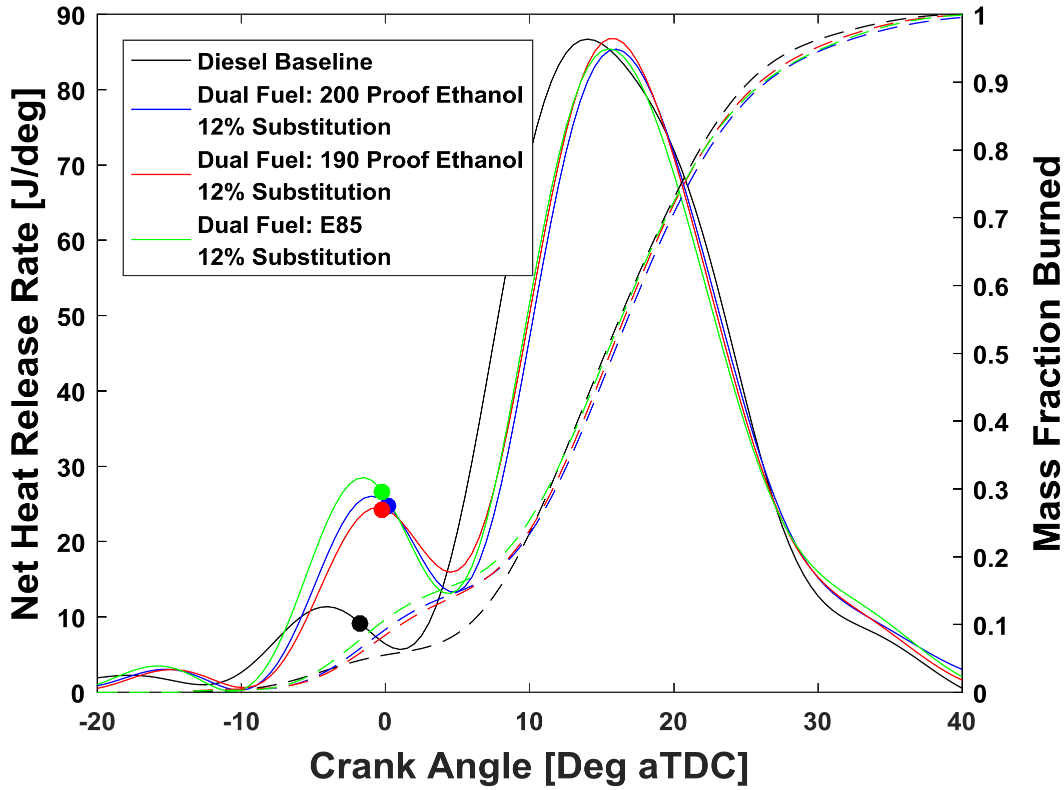

Figure 36. Traces from cylinder 6 with the engine operating at 1800 rpm and 75% torque. Solid lines represent the net heat release rate and the dashed lines are the mass fraction burned. Main diesel SOI for the diesel baseline, 200 proof dual fuel, 190 proof dual fuel, and E85 dual fuel shown by the heavy, colored circles were 1.9 °BTDC, -0.2 °BTDC, 0.2 °BTDC, and 0.2 °BTDC, respectively.

fuel heat release, and a delayed diesel fuel heat release of approximately 2.5 crank angle degrees (CAD). The delayed diesel fuel heat release can be explained by the change in the mSOI between diesel fuel and dual fuel test points. If a well-mixed air and fuel volume is assumed then the dual fuel heat release can be considered a premixed combustion event.

The crank angle at which 50% and 10% of the total heat release occurs is defined as CA50 and CA10. Table 9 contains CA10 and CA50 values for diesel fuel and 200 proof dual fuel test points. The initial dual fuel premixed combustion heat release is realized when comparing the CA10 values of diesel fuel and ethanol premixed combustion. Figure 38 shows the how the NHRR and MFB progress as diesel

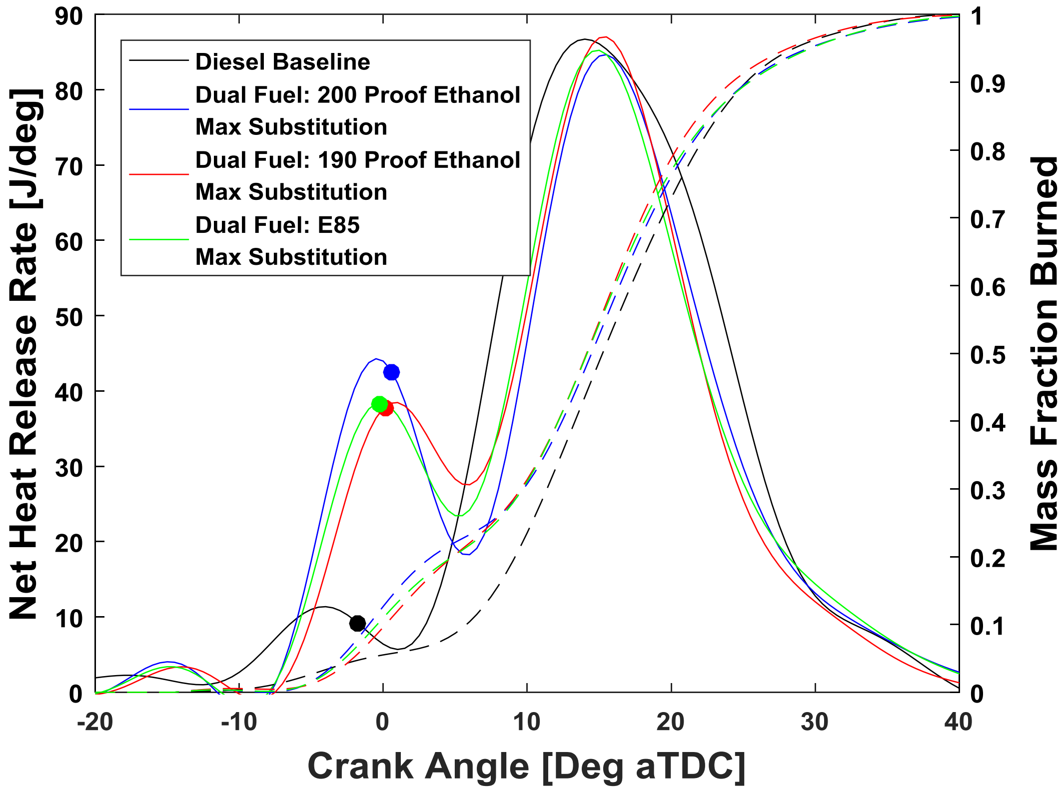

Figure 37. Maximum diesel substitution traces from cylinder 6 with the engine operating at 1800 rpm and 75% torque. Solid lines represent the net heat release rate and the dashed lines are the mass fraction burned. Main SOI for the diesel baseline, 200 proof dual fuel, 190 proof dual fuel, and E85 dual fuel shown by the heavy, colored circles were 1.9 °BTDC, -0.6 °BTDC, -0.1 °BTDC, and 0.2 °BTDC, respectively.

Table 9. CA10 and CA50 comparisons for increasing diesel substitution at intermediate speed – 75% torque

	mSOI (dBTDC)	CA10 (dATDC)	CA50 (dATDC)
Diesel Baseline	1.8	6	15.5
DF:200 - 12% Sub	-0.2	0.5	16
DF:200 - 25% Sub	-0.6	-1	14.5

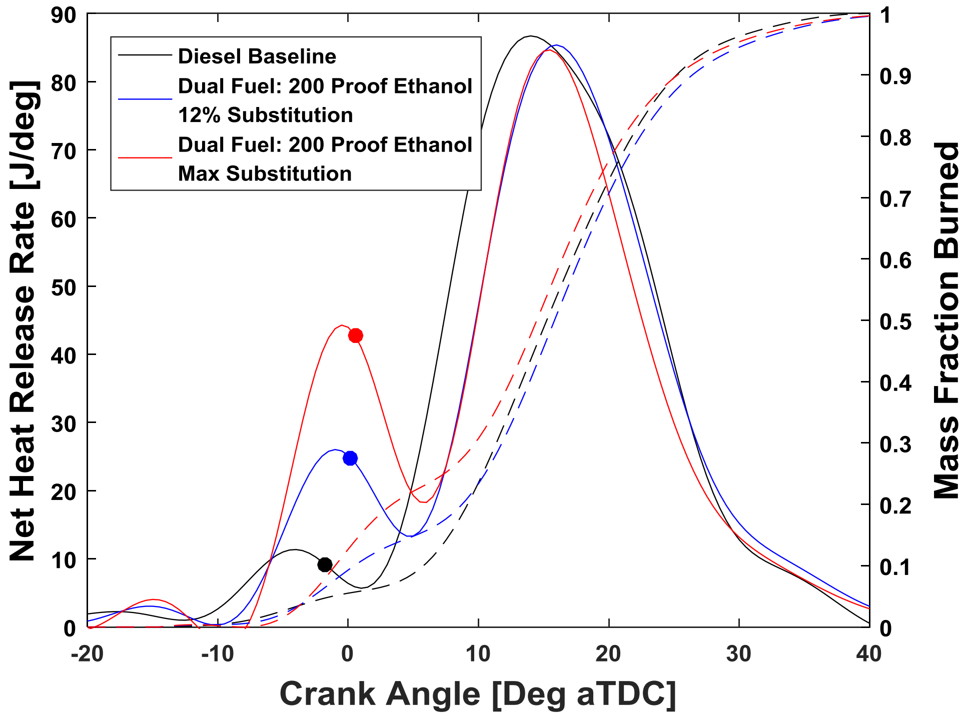

Figure 38. Net heat release rate and mass fraction burned as diesel substitution increases from 12% to 25%. Solid lines represent the net heat release rate and the dashed lines are the mass fraction burned. Diesel fuel main SOI is shown in column one of Table 9.

substitution increases. Notably, the NHRR for diesel fuel does not decrease as less diesel fuel is consumed, but the premixed NHRR increases with an increase in dual fuel consumption. NHRR and MFB while the engine was operating at 2500 rpm and 50% torque are shown in Figure 39. When compared to the 1800 rpm and 75% torque 200 proof dual fuel test case, the diesel mSOI timing occurs on average 1.4 CAD earlier, but the dual fuel NHRR peak occurs 9.5 CAD at -9 °BTDC. This delay in the NHRR peak is preferred as nearly all of the heat release occurred after top dead center which results in more work being done on the cylinder during the combustion process.

The 200 proof ethanol dual trace has the largest NHRR value of approximately 63 J/deg. The 200 proof dual fuel test also had the highest diesel substitution, 43%, while the 190 proof and E85 dual fuel tests

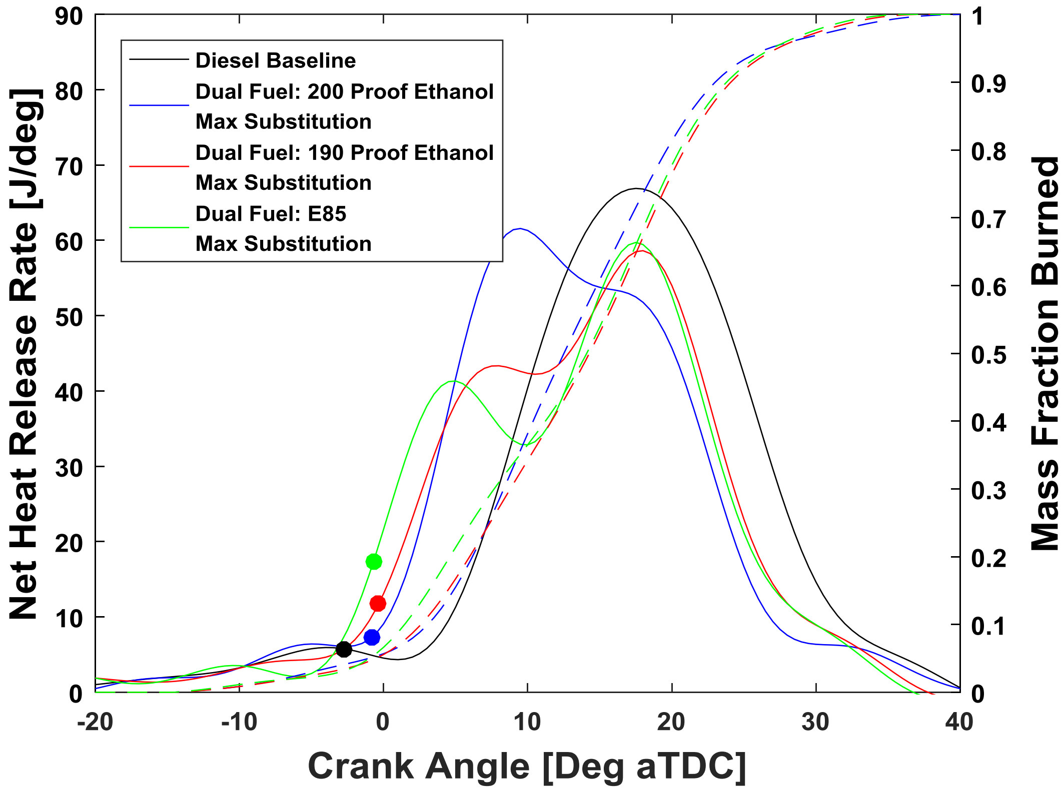

Figure 39. Maximum diesel substitution traces from cylinder 6 with the engine operating at 2500 rpm and 50% torque. The solid lines are net heat release rate and the dashed lines are the mass fraction burned. Main SOI for dual fuels 200 proof ethanol, 190 proof ethanol, and E85 shown by the colored circles were 0.8 °BTDC, 0.4 °BTDC, and 0.7 °BTDC, respectively.

allowed for a diesel substitution of 37% and 39%, respectively before audible engine knock occurred. The higher diesel substitution limit and delayed heat release compared to E85 dual fuel tests can be attributed to the research octane number (RON) of 200 proof ethanol. According to Heywood [16] the RON of 200 proof ethanol is approximately 107. ASTM D5798-15 sets requirements for fuel blends of ethanol and gasoline for on road vehicles, and the allowable ethanol content in an E85 blend can vary between 51 and 83 volume percent. The ethanol volume percent in the E85 fuel used for this study was 85% and thus any published RON values would not be applicable, but it can be inferred that the RON of E85 fuel would be lower than that of 200 proof ethanol.

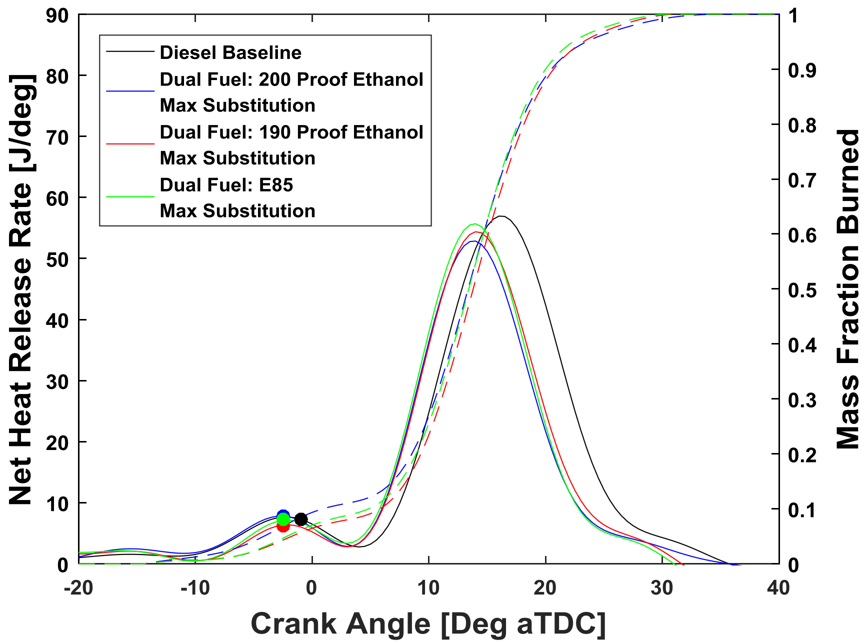

Figure 40. Maximum diesel substitution traces from cylinder 6 with the engine operating at 2500 rpm and 25% torque. Solid lines are net heat release rate and dashed lines are the mass fraction burned. Main diesel SOI shown by the heavy, colored circles was 2.5 °BTDC for all dual fuel test points and 1°BTDC for the diesel baseline test point.

Figure 40 shows the NHRR and MFB while the engine was operating at 2500 rpm and 25% torque. Diesel fuel substitution at this engine operating point was limited by non methane hydrocarbon (NMHC) emissions requirements. The substitution limits for 200 proof ethanol, 190 proof ethanol, and E85 fuel were 26%, 24%, and 25% respectively. The NHRR and MFB traces of each dual fuel test closely resemble the diesel traces because of the excess amounts of dual fuel not being burned in the combustion process.

4.4 INDICATED MEAN EFFECTIVE PRESURE (IMEP)

Engine mean effective pressure is defined as the work done per cycle divided by the volume displaced per cycle. IMEP includes work delivered to the engine crankshaft and the work required to overcome frictional and pumping losses. The general form of the equation for IMEP is shown in Equation

2 where n_R is the number of crank revolutions for each expansion stroke per cylinder, V_d is the volumetric displacement, N is the crankshaft rotational speed, and P_i is the net power. [16]

$$IMEP = \frac{P_i n_R}{V_d N} \tag{2}$$

The coefficient of variation defined in Equation 3 measures IMEP cycle to cycle variability, and quantifies the stability of combustion processes where σ_{IMEP} is the standard deviation of the data cycles

$$COV_{IMEP} = \frac{\sigma_{IMEP}}{IMEP} * 100 \tag{3}$$

collected. According to Heywood [16] noticeable engine operation problems arise when COV_{IMEP} exceeds a value of 10 percent. Tables 10 through 12 show 500 cycle averages of cylinder IMEP and COV_{IMEP} for various engine test points, dual fuels, and diesel substitutions. The maximum COV_{IMEP} of 6.1% occurs during the diesel baseline test at 2500 rpm and 25% torque, and is well below the 10% COV_{IMEP} limit. Nearly every dual fuel test point in Table 10 and Table 12 showed an improvement in COV_{IMEP} when compared to the diesel baseline. Dual fuel COV_{IMEP} values in Table 11 are markedly increased from the diesel fuel baseline, but are still below the 10% limit.

Table 10. IMEP and COV_{IMEP} for cylinders 3, 5, and 6 while the engine was operating at 1800 rpm and 75% torque.

		IMEP (kPa)			COV (%)		
Dual Fuel	**Diesel Substitution**	**Cylinder 6**	**Cylinder 3**	**Cylinder 5**	**Cylinder 6**	**Cylinder 3**	**Cylinder 5**
Diesel Baseline	----	1888	1895	1933	2.1	2.2	1.6
200 Proof Ethanol	12%	1819	1833	1886	1.5	1.5	1.1
200 Proof Ethanol	25%	1853	1791	1827	1.7	1.7	2.5
190 Proof Ethanol	11%	1787	1826	1806	1.6	1.6	1.3
190 Proof Ethanol	25%	1776	1788	1783	2.2	1.7	2.3
E85 Fuel	12%	1883	1928	1947	1.9	1.5	1.3
E85 Fuel	24%	1815	1801	1852	2.4	2.0	2.0

Table 11. IMEP and COV_{IMEP} for cylinders 3, 5, and 6 while the engine was operating at 2500 rpm and 50% torque.

		IMEP (kPa)			COV (%)		
Dual Fuel	**Diesel Substitution**	**Cylinder 6**	**Cylinder 3**	**Cylinder 5**	**Cylinder 6**	**Cylinder 3**	**Cylinder 5**
Diesel Baseline	----	1401	1429	1377	3.3	2.7	3.1
200 Proof Ethanol	43%	1454	1376	1444	2.9	4.6	2.9
200 Proof Ethanol	37%	1420	1381	1417	3.6	4.5	2.7
E85 Fuel	39%	1400	1411	1368	3.6	4.4	3.9

Table 12. IMEP and COV_{IMEP} for cylinder 3, 5, and 6 while the engine was operating at 2500 rpm and 25% torque.

		IMEP (kPa)			COV (%)		
Dual Fuel	**Diesel Substitution**	**Cylinder 6**	**Cylinder 3**	**Cylinder 5**	**Cylinder 6**	**Cylinder 3**	**Cylinder 5**
Diesel Baseline	----	899	995	832	6.1	4.5	4.8
200 Proof Ethanol	26%	841	884	874	2.7	4.2	2.5
190 Proof Ethanol	24%	827	869	868	2.3	3.6	1.8
E85 Fuel	25%	831	887	866	2.2	4.0	1.9

4.5 KNOCK ANALYSIS

As described in section 3.4.3, knock analysis was performed on all combustion data collected. The metric used to quantify knock was knock index (KI) which was defined in previous work by Wise [21] as the summation of discrete knock magnitudes over a set combustion cycle count. The cycle count used in this study was 50. Figure 41 shows combustion pressure traces while the engine was operating at 1800 rpm and 75% torque using 200 proof ethanol as the dual fuel. The engine operating using only diesel fuel corresponds with a KI value of 0. This KI value represents no engine knock. The KI value of 194 in Figure 41 is analogous to audible engine knock and 26% diesel substitution. Dual fuel flow was decreased until audible knock was no longer present, and the corresponding diesel substitution at this point, 25%, was considered the maximum allowable substitution. This point was considered to be an acceptable operating point and is represented in Figure 41 with a KI value of 91. A KI value of 10 was achieved at a 12% diesel substitution rate. Table 13 shows the variability in KI for cylinder 3, 5, and 6 using different ethanol fuels and engine operating points. Audible knock was observed at each of these test points. KI values for cylinder 3 were consistently lower than that of cylinder 5 and 6. This could be due to poor mixing of ethanol and air resulting in uneven distribution of ethanol across all cylinders. Cylinder 3 KI values in Table 13 were also lower than the acceptable KI value of 114 shown in Figure 41. It can be inferred that during audible knock events not all cylinders were knocking. The lowest KI value corresponding to audible engine knock was 128, and occurred using E85 as a dual fuel while the engine was running at 1800 rpm and 75% torque.

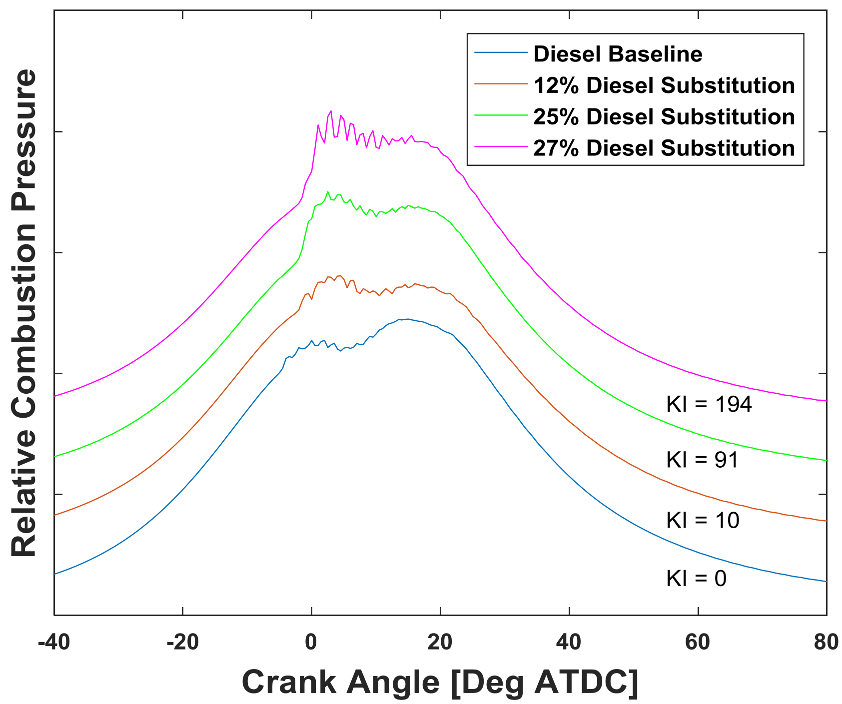

Figure 41. FFT Knock pressure traces and corresponding KI values for cylinder 6 while the engine was operating at 1800 rpm and 75% torque with 200 proof ethanol as a dual fuel.

Table 13. KI values for audible knock events

		Knock Index (KI)		
Engine Operating Point	**Dual Fuel**	**Cylinder 6**	**Cylinder 3**	**Cylinder 5**
Rated Speed - 50% Torque	200 Proof	229	96	184
Intermediate Speed - 75% Torque	200 Proof	194	52	186
Rated Speed - 50% Torque	E85	231	69	146
Intermediate Speed - 75% Torque	E85	128	41	106
Rated Speed - 50% Torque	190 Proof	158	61	128
Intermediate Speed - 75% Torque	190 Proof	221	57	155

CHAPTER 5
EMISSIONS ANALYSIS

5.1 TIER 4 FINAL REQUIREMENTS

The ISO 8178 standard for engine exhaust emission measurement uses weighted averages of eight individual emission measurements to calculate a final emission number. Three engine load points were selected in this work so a final emissions number for ethanol premixed combustion cannot be calculated per ISO 8178. However, it was decided that a limiting factor for diesel substitution would be that emissions at any load calculated in real time should not exceed the Tier 4 Final EPA requirement for the weighted average brake specific emission. This would ensure that in a comprehensive ISO 8178 test a single test point would not have a detrimental effect on the overall weighted average emission number. Figures shown in this chapter, where applicable, show the Tier 4 Final nonroad emission requirement.

It is also recognized that engine parameters such as exhaust gas recirculation flow rate, diesel injection timing, charge pressure, and diesel exhaust fluid (DEF) dosing rate have a significant impact on exhaust emissions. These parameters were monitored but were not controlled or manually adjusted during this study. Any adjustment to the aforementioned parameters or others was done independently by the engine ECU. Where needed these values will be reported with exhaust emission results.

5.2 GASEOUS EMISSION ANALYSIS

Gaseous emissions of NO_x, CO, and NMHC were calculated using Equation 4, and PM emissions were calculated using Equation 5.

$$m_i = \frac{m_f \alpha y_i M_i}{M_f \sum (y_i \alpha_i)} \tag{4}$$

Where

m_f = total fuel consumption

α = weighted total fuel carbon number (including dual fuel)

y_i = species concentration

M_i = species molecular weight

M_f = weighted molecular weight of the fuel (including dual fuel)

α_i = carbon number of selected emission species.

$$m_{PM} = m_{ex} f_{PMfs}(DR + 1) \tag{5}$$

Where

m_{ex} = engine exhaust mass flow rate

f_{PMfs} = mass fraction of PM in filter sample flow

DR = dilution ratio.

Error bars shown on the data in the figures of this section define the uncertainty associated with the repeatability of the data collected. Four test days were conducted to gather the data presented in this work, and on each of those days a repeated engine test point at 75% torque and intermediate speed was conducted. Thus, the number of repeated tests used to derived the repeatability was four. It is recognized that emissions measurements also include linearity and other uncertainties, but these were not included in the reported uncertainty.

Figure 42 shows the variation of NO_x emissions while the engine was operating at intermediate speed and 75% torque. Data was collected at a common diesel substitution point of 12%, and the maximum diesel substitution for 200 proof ethanol, 190 proof ethanol, and E85 fuel was 25%, 25%, and 24%, respectively. Pre-catalyst dual fuel NO_x emissions at 12% diesel substitution decreased by approximately 1 g/bkW-hr when compared to standard diesel fuel. However, when substitution was increased to the maximum allowable level ethanol premixed combustion NO_x emissions increased 0.4-1 g/bkW-hr. EGR flow at respective dual fuel types and diesel substitutions are shown in Figure 43. At 12% diesel substitution average dual fuel EGR flowrates increased by 0.35 kg/min, and the diesel mSOI was retarded by approximately two CAD. It is well documented [16] that increased EGR flow rates and retarded injection timing reduced NO_x emissions. Post catalyst emissions of ethanol premixed combustion at 12% diesel substitution show a significant decrease with respect to the pre catalyst concentrations. The Tier 4 Final requirement for NO_x for this class of engine is 0.4 g/bkW-hr. The highest post catalyst NO_x

concentrations were found for 200 proof ethanol at a level of 0.06 g/bkW-hr. A similar trend of high pre catalyst NO_x emissions and low post catalyst NO_x emissions was observed when the diesel substitution at this test point was increased to approximately 25% across all dual fuel tests. However, pre catalyst dual fuel NO_x concentrations were higher when compared to diesel fuel. Figure 43 shows that at maximum diesel substitution dual fuel EGR flow rates were, on average, 0.35 kg/min lower than diesel fuel EGR flow rates. In addition Table 15 shows the total charge flow of diesel fuel and all dual fuels while at this test point. At maximum diesel substitution average dual fuel charge flow decreases by 8%.

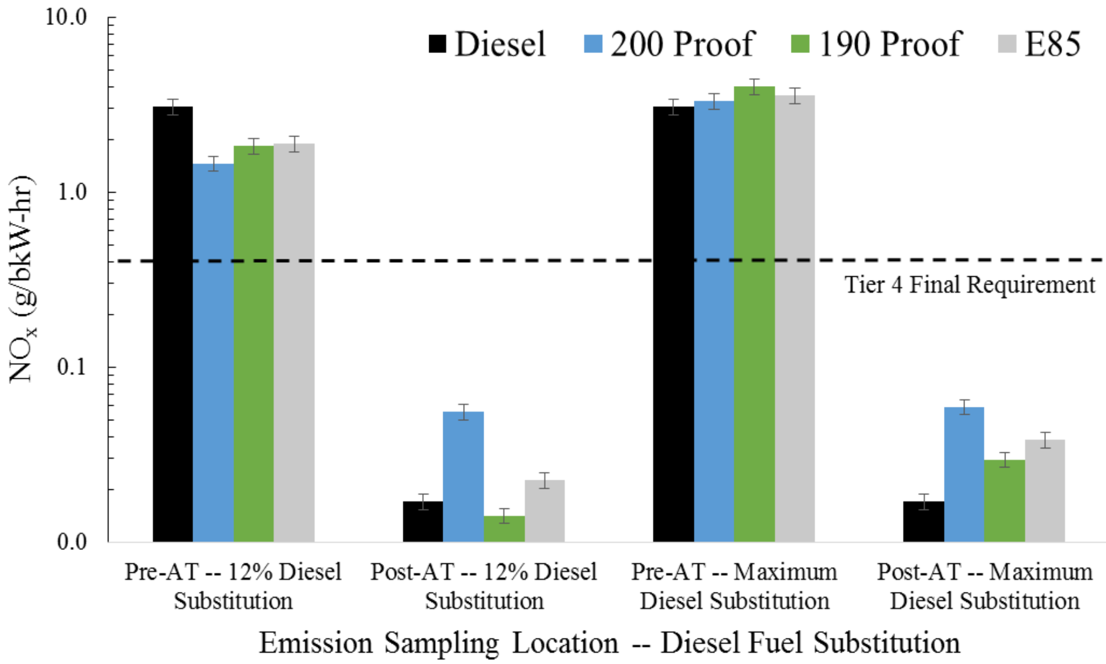

Figure 42. NO_x emissions sampled pre- and post-catalyst while the engine was operating at intermediate speed – 75% torque.

Table 14. Diesel mSOI while the engine was operating at intermediate speed – 75% torque.

	Diesel mSOI (dBTDC)			
	Diesel	200 Proof	190 Proof	E85
12% Diesel Substitution	1.8	-0.2	0.2	0.2
Maximum Diesel Substitution	1.8	-0.6	-0.1	0.2

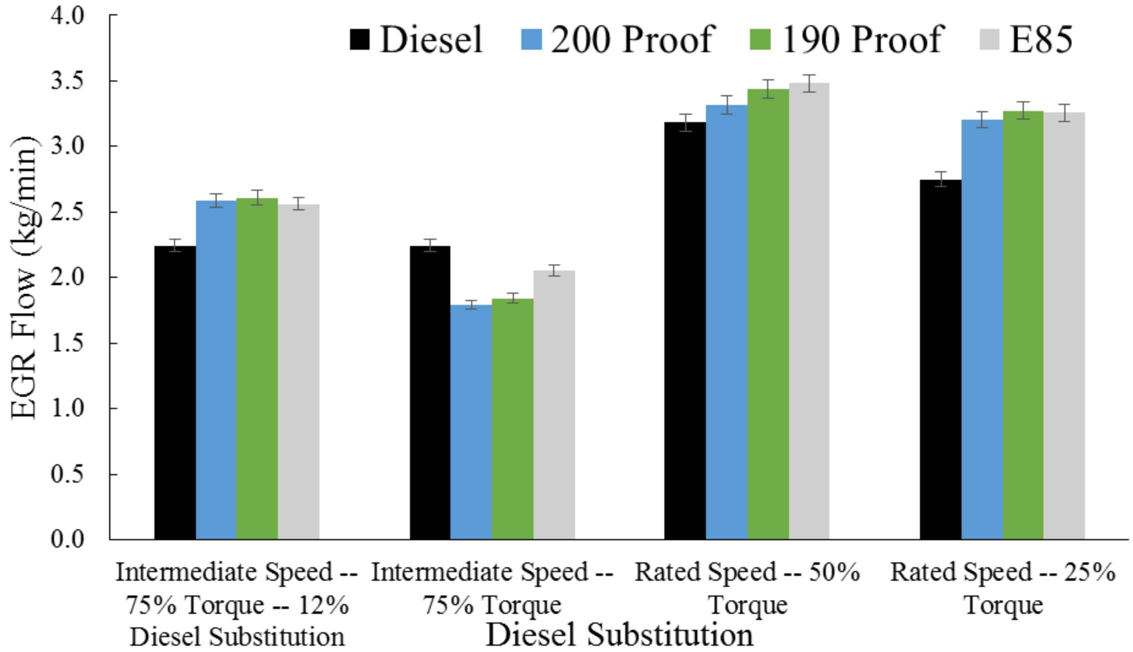

Figure 43. EGR Flow at varied engine speed and torque.

If it is assumed that the dual fuel is gaseous and well mixed with air as it enters the cylinder and that this mixture can be modeled as an ideal gas then the in cylinder temperature would increase due to a lower total volume of air in the cylinder. Post catalyst dual fuel NO_x emissions at maximum diesel substitution show the current after treatment system is capable of lowering these emissions to well below the requirement. However, the DEF dosing rate required to mitigate these emissions was higher when compared to 12% diesel substitution and diesel only combustion. The average DEF dosing rates were 1150, 565, and 926 g/hr for maximum diesel substitution, 12% diesel substitution, and diesel only combustion, respectively.

Table 15. Engine charge flow while operating at intermediate speed – 75% torque.

	Charge Flow (kg/min)			
	Diesel	200 Proof	190 Proof	E85
12% Diesel Substitution	13.0	12.9	13.1	12.9
Maximum Diesel Substitution	13.0	12.1	12.2	12.0

The non-road Tier 4 Final CO emission requirement for the test engine is 3.5 g/kw-hr. Figure 44 includes data taken while the engine operated at intermediate speed – 75% torque, Emissions were collected pre and post catalyst, and diesel substitution was increased to approximately 25%. Dual fuel pre catalyst emissions at 12% and maximum diesel substitution increased by a factor of 6 and 8.5, respectively, but were below the Tier 4 limit. The DOC was effective in reducing diesel fuel and dual fuel CO emissions. At high engine load low CO concentrations are expected due to a more complete combustion. Figure 44 affirms this, showing that pre catalyst emission levels fall below the required level. However, all pre catalyst dual fuel emissions did increase with respect to diesel fuel.

The Tier 4 Final limit for NHMC is 0.19 g/kW-hr. Total hydrocarbon emissions were measured using the 5-Gas analyzer described in Chapter 3, but the regulated emission excludes methane emissions. Methane emissions were measured using the FTIR spectrometer. This system measures gaseous

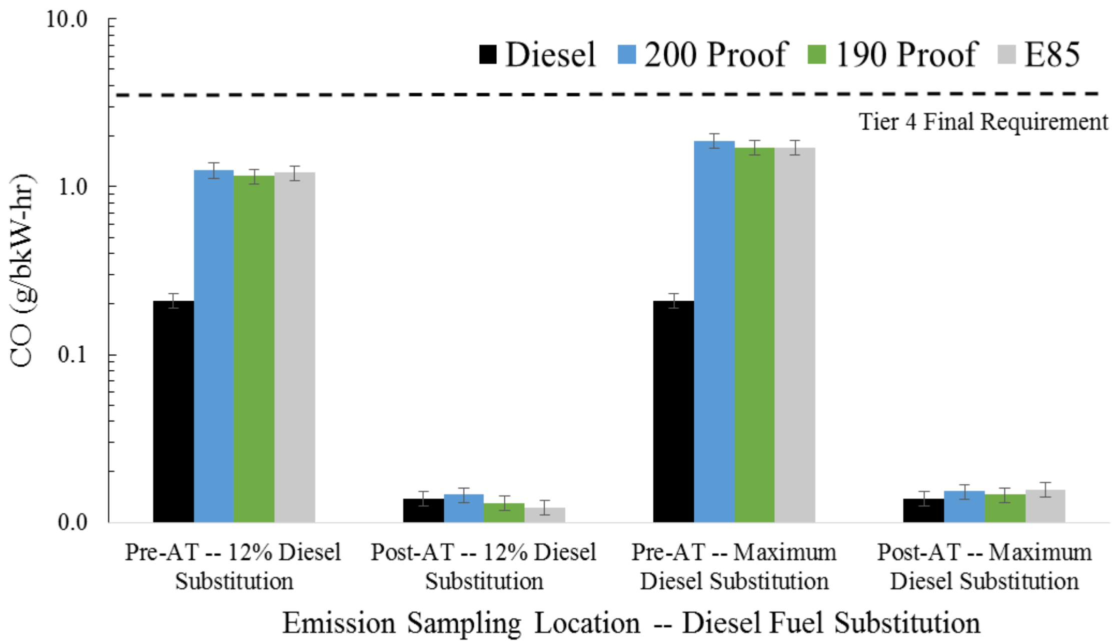

Figure 44. CO emissions sampled pre- and post-catalyst while the engine was operating at intermediate speed – 75% torque.

$$n_{dry} = n_{wet} * \left(\frac{100}{(100 - \%H_2O)}\right) \tag{6}$$

Where

$\%CO_2$ = concentration of carbon dioxide on a dry basis

% CO = concentration of carbon monoxide on a dry basis

%THC = total hydrocarbons on a dry basis

emissions as ‘wet’ emissions, but the 5-gas system used measures ‘dry’ emissions. Wet methane measurements were converted to dry measurements using Equation 6.

Figure 45 compares dual fuel NMHC emissions to diesel only emissions at intermediate speed -75% torque. Dual fuel pre catalyst emissions were above the Tier 4 limit, but similar to NO_x and CO emissions the catalyst system was able to reduce emissions below the required level at 12% diesel substitution and at maximum diesel substitution. Pre catalyst dual fuel emissions were also, on average, four times higher than diesel fuel NMHC emissions, and seven times higher than diesel fuel NMHC emissions at 12% and maximum diesel substitution, respectively.

Premixed dual fuel and air entering the cylinder increases NMHC emissions due to unburned fuel residing in the cylinder prior to ignition. Unburned hydrocarbon emissions can be produced from fuel in cylinder crevice volumes such as cylinder ring clearances and head gasket spaces [16]. Premixed fuel and air near the cylinder boundaries can also remain unburned due to flame quenching at the cylinder wall. Another source of unburned hydrocarbon emissions commonly found in spark ignited engines is liquid fuel that impinges on the surface of the cylinder.

The unburned hydrocarbon production mechanisms described above may be a significant source of this emissions in the ethanol premixed combustion strategy used during this work. Post catalyst emissions using 190 proof ethanol remained much higher than diesel fuel and other ethanol premixed combustion tests. These emissions

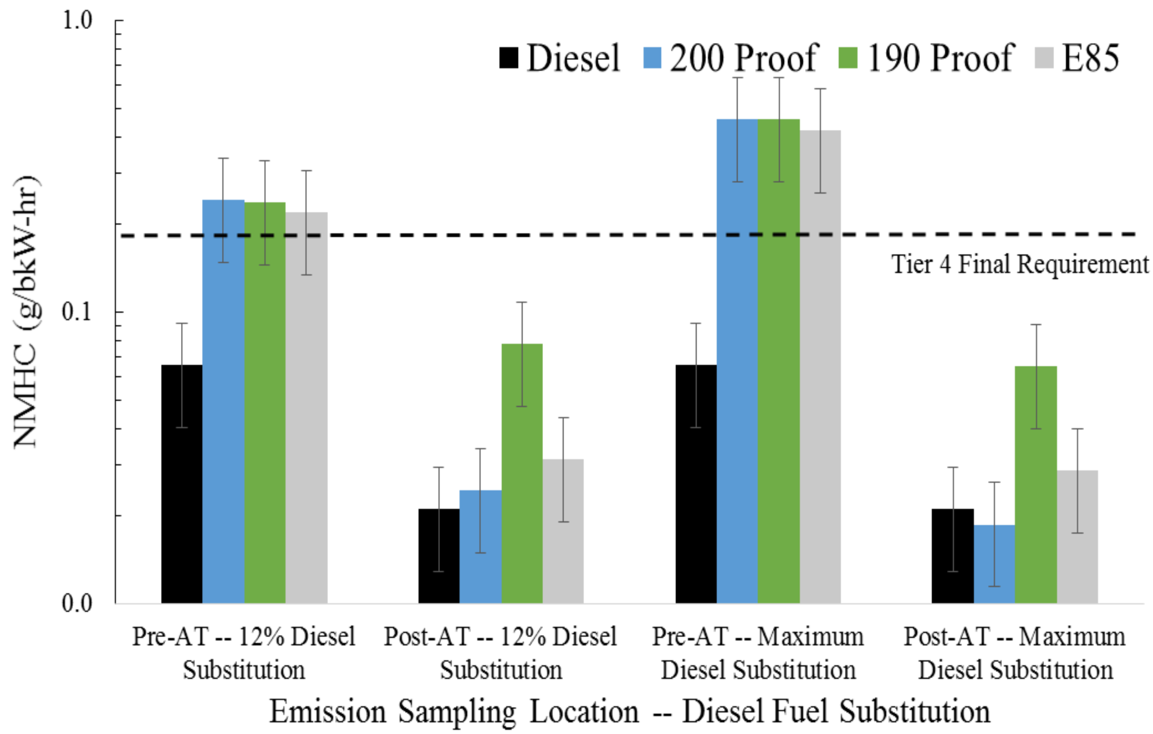

Figure 45. NMHC emissions sampled pre- and post-catalyst while the engine was operating at intermediate speed – 75% torque.

were on average two times higher than E85 and 200 proof dual fuel tests and three times higher than diesel fuel combustion.

Particulate matter emissions reported in Figure 46 were taken while the engine was operating at intermediate speed – 75% torque. These results shows similar trends as the NO_x emissions results displayed in Figure 42. At 12% diesel substitution pre catalyst dual fuel PM emission increased significantly compared to diesel fuel only combustion. This result was unexpected as it was theorized that less diesel fuel combustion would results in lower PM emissions. Post catalyst dual fuel results at 12% diesel substitution also increased when compared to diesel fuel and were above the Tier 4 Final limit for this emission. Increasing diesel substitution had an inverse effect on PM emissions where 200 proof and 190 proof dual fuel tests had lower PM emissions than diesel fuel. E85 dual fuel tests showed higher PM emissions when compared to diesel fuel, but overall were lower than the 12% diesel substitution test. This unexpected relationship between diesel substitution and PM emissions can be explained partially by examining Figure 43. Higher EGR rates can correspond to higher PM emissions due to the lower total volume of air able to oxidize carbon in the cylinder. Post catalyst results at this substitution showed mixed results as 200 proof ethanol PM emissions increased, but 190 proof and E85 emissions were mitigated by the aftertreatment system below the limit. The post catalyst 200 proof diesel fuel result is inconsistent with other dual fuel results, and is questionable due to its inconsistency with all other dual fuel PM trends and elemental particulate matter reduction theory. However, measurements made using Teflon and Quartz filters showed an increase in total PM collected. These results will be further detailed in Chapter 5 section 3. Excluding the 200 proof post catalyst maximum diesel substitution result and the pre catalyst 12% diesel substitution result Figure 46 shows that dual fuel E85 has the highest PM emission followed by 190 proof and 200 proof.

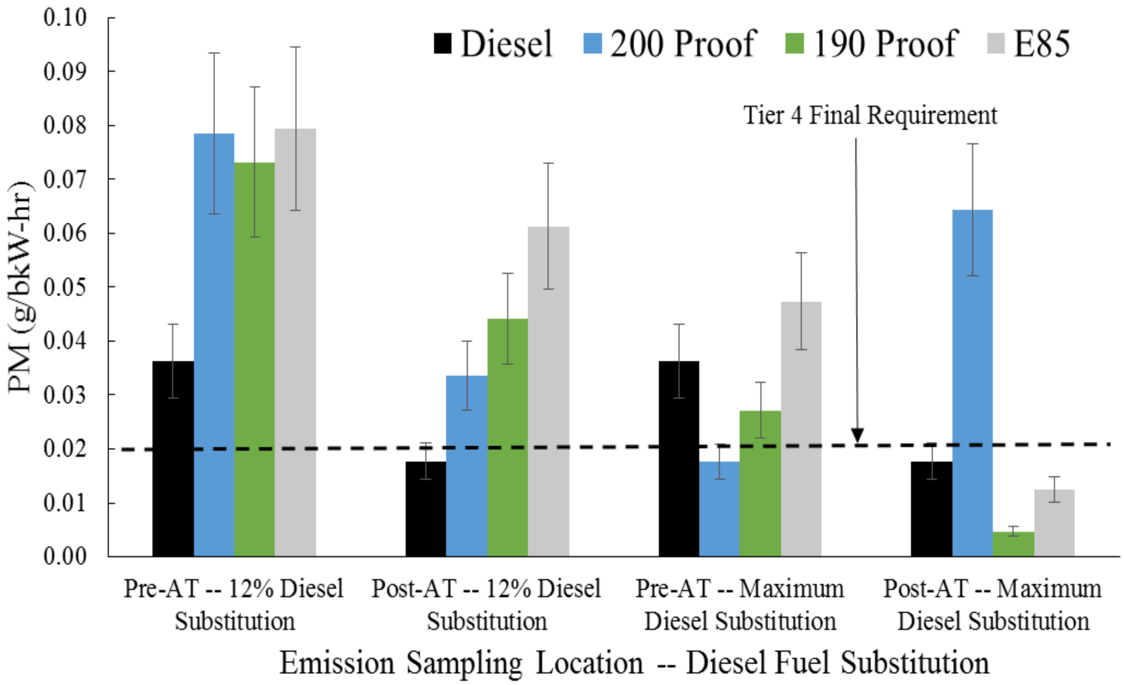

Figure 46. Particulate matter emissions while the engine was operating at intermediate speed – 75% torque. Particulate cutoff size was 10 µm (PM10).

Figure 47 shows the relationship between engine speed and torque and NO_x emissions. Due to lack of test time diesel fuel baseline emissions at rated speed – 50% torque and rated speed – 25% torque were not collected and thus Figures 47-50 only include dual fuel maximum diesel substitution post catalyst emissions. These figures show data as reported by the 5 Gas emission measurement system. As engine load decreases from 142 kW (intermediate speed – 75% torque) to 64 kW (rated speed – 25% torque) post catalyst NO_x emissions increase, but the catalyst system reduces emissions below the required limit for all dual fuel tests except the 200 proof rated speed – 25% torque test. The test engine was outfitted with pre and post catalyst NO_x sensors. On average these sensors measured within 8 ppm of FTIR NO_x measurements across all tests. The pre and post catalyst sensor data is shown in Figure 48 to compare pre and post catalyst NO_x data for varied engine speed and load.

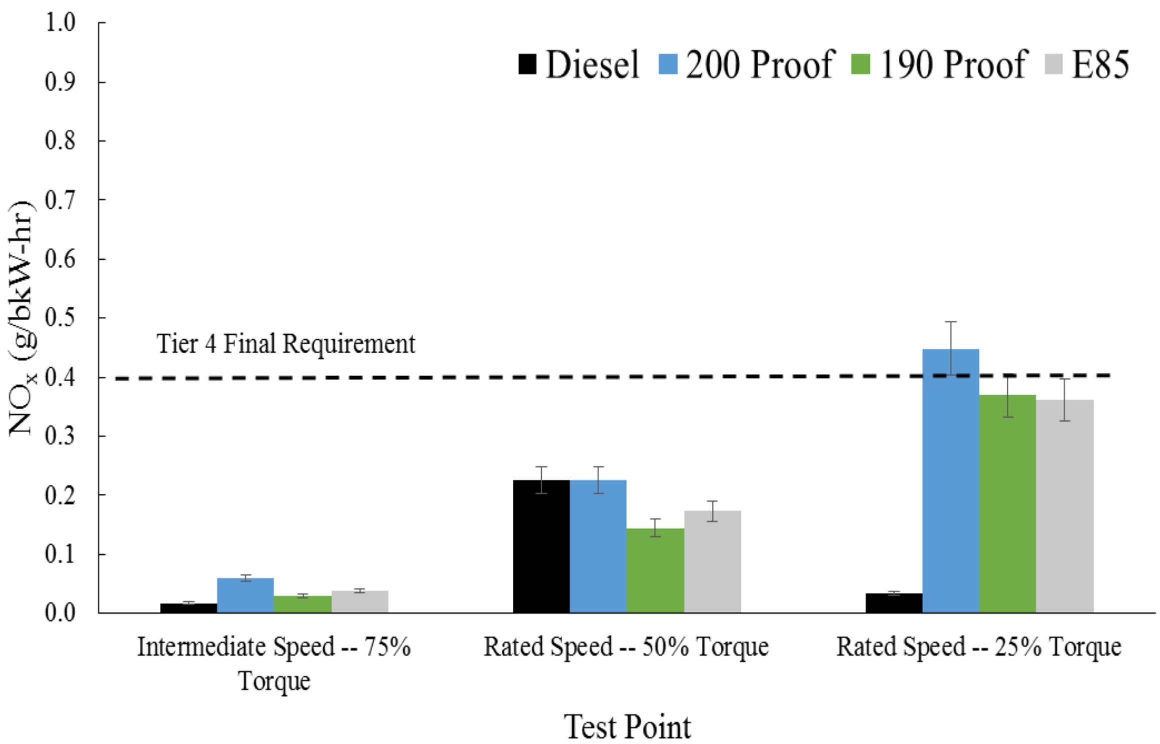

Figure 47. Post catalyst NO_x emissions at maximum diesel substitution and varied engine speed and load.

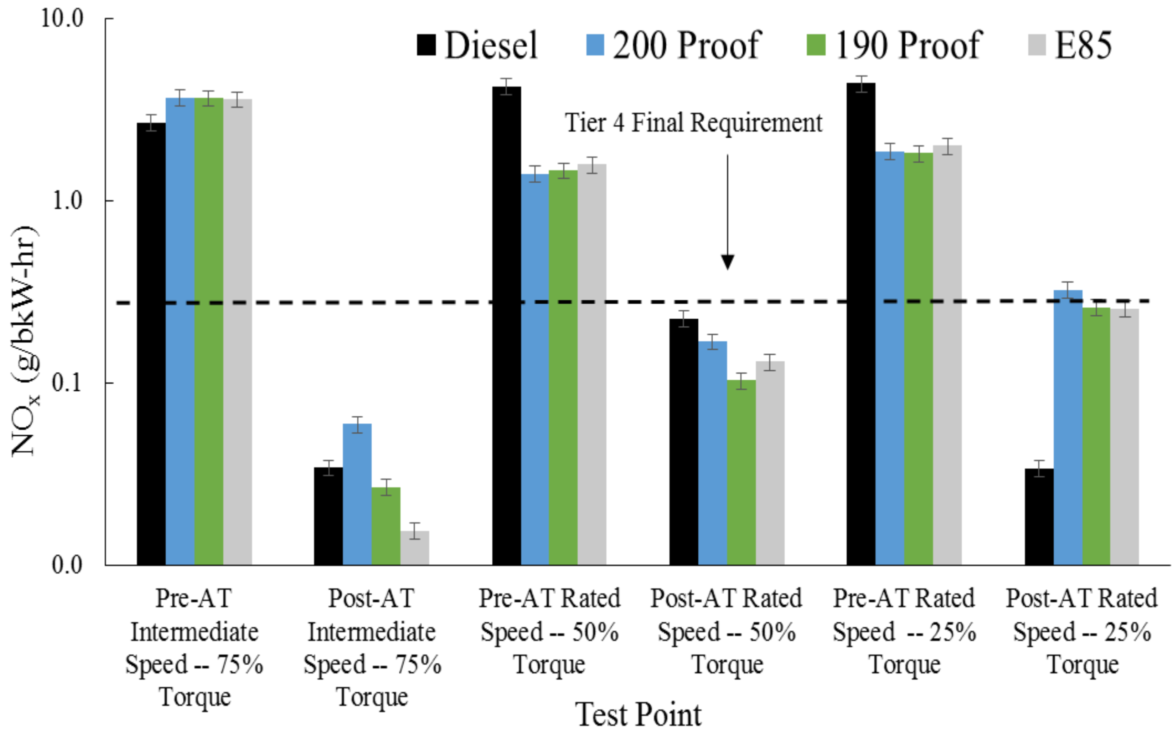

Figure 48. Calterm pre and post catalyst NO_x data at varied engine speed and load.

Post catalyst CO emissions at maximum diesel substitution are shown in Figure 49. Clearly, the diesel oxidation catalyst is able to reduce these emissions well below the limit for the test points used in this work. An increase in CO emissions corresponded to a decrease in engine load, which was expected due to incomplete combustion at lower engine loads. NMHC emissions shown in Figure 50 were also well below the Tier 4 Final limit with the exception of the 190 proof dual fuel test at rated speed – 25% torque. Figure 35, presented earlier, displayed the combustion trace for this test case, and despite the maximum diesel substitution being 25% there was no observable premixed ethanol combustion event. Thus, it can be inferred that the increased NMHC levels at rated speed – 25% torque are due to lack of ethanol premixed combustion.

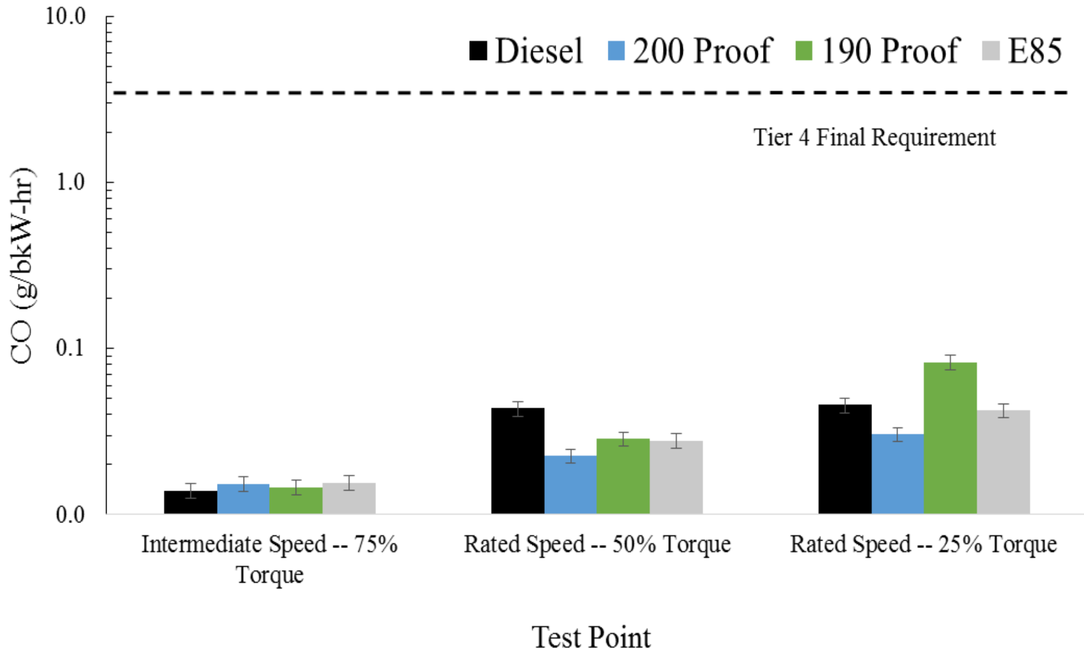

Figure 49. Post catalyst CO emissions at maximum diesel substitution and varied engine speed and load

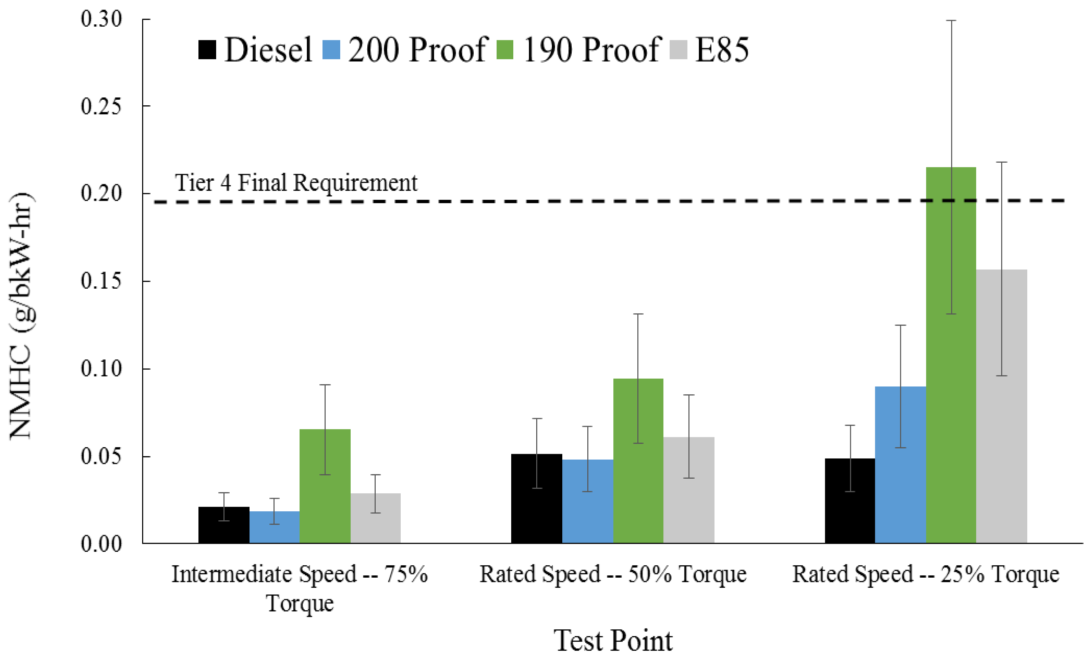

Figure 50. Post catalyst NMHC emissions at maximum diesel substitution and varied engine speed and load

Figure 51 shows PM emissions at varied engine speed and torque. It was expected that PM emissions would decrease as engine torque decreased and speed increased, but Figure 51 clearly shows the opposite effect for all dual fuels tested. The average EGR flow rates at rated speed – 50% torque and rated speed 25% torque were 3.4 and 3.3 kg/min respectively, and the flow rate at intermediate speed – 75% torque was on average 1.9 kg/min. This increased EGR flow rate may account for the increased PM emissions at lower engine loads.

Formaldehyde is a known carcinogen, which can be formed by partial combustion. It is not regulated for compression ignition engines, but when using oxygenated fuels such as ethanol, incomplete combustion at low engine load can lead to production of formaldehyde during the combustion process. This emission was measured during each engine test using a FTIR.

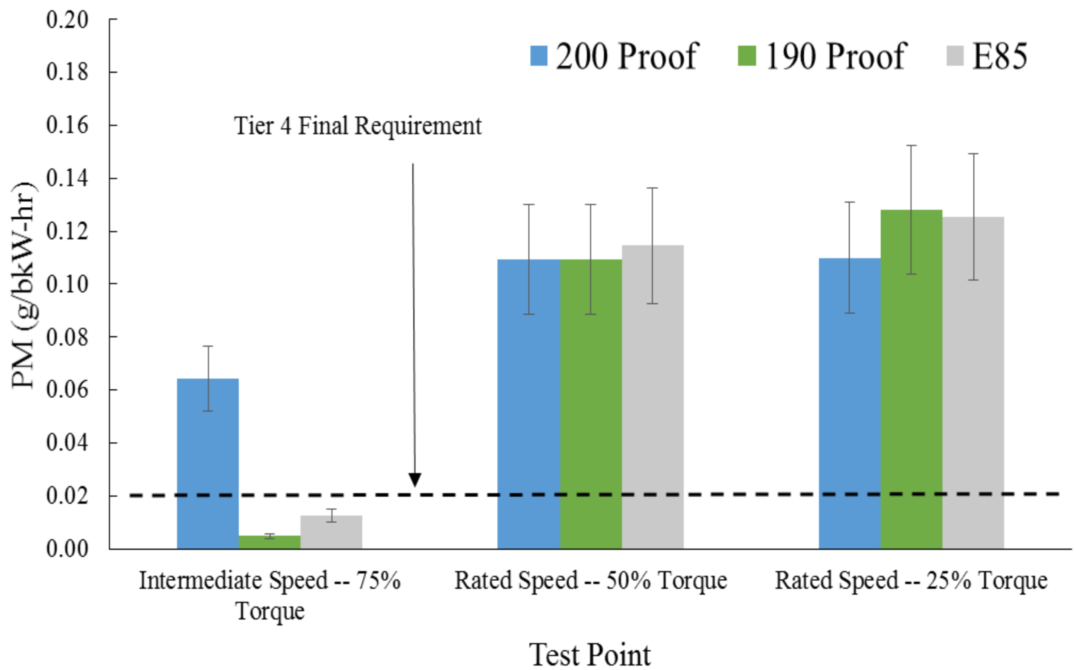

Figure 51. Post catalyst PM emissions at maximum diesel substitution and varied engine speed and load.

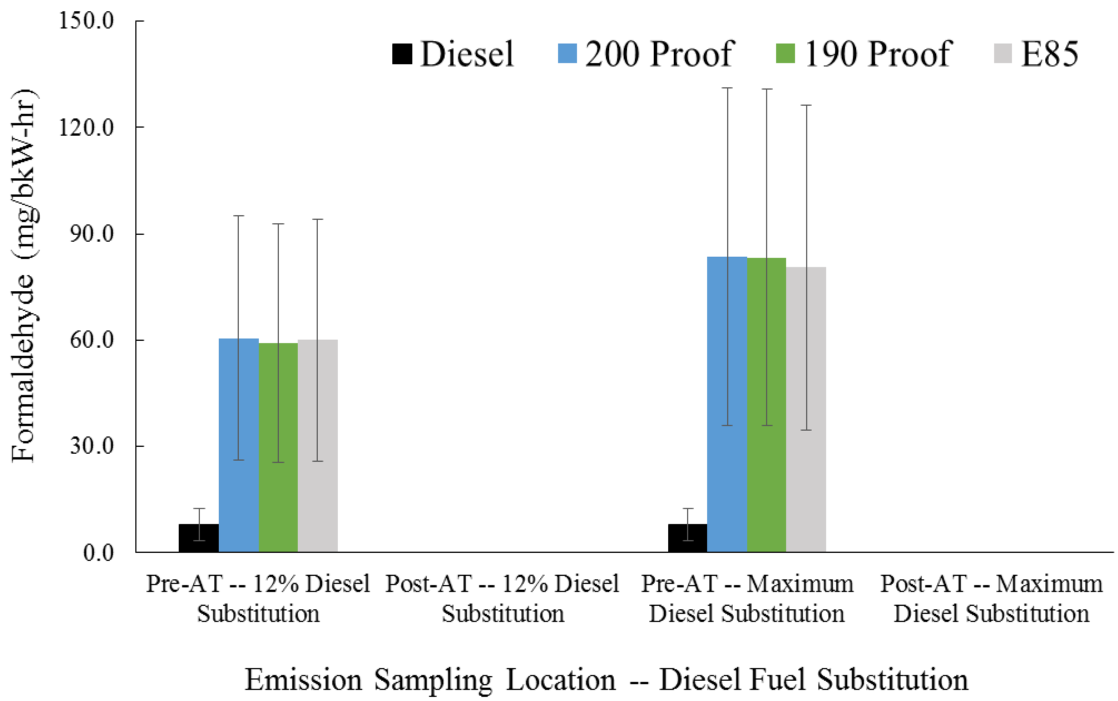

Figure 52. Formaldehyde emissions while the engine was operating at intermediate speed – 75% torque.

These emissions were approximately two orders of magnitude lower than regulated emissions of NO_x, CO, NMHC, and PM so the concentration has been displaced in units of mg/bkW-hr. Pre catalyst sampling showed that ethanol premixed combustion resulted in substantially increased formaldehyde emissions, but the aftertreatment system was able to mitigate these emissions to nearly undetectable levels. Figure 53 shows post catalyst formaldehyde emissions measured in mg/bkW-hr as a function of engine speed and torque. Only when using 190 proof ethanol as a dual fuel at rated speed – 25% were any measurable emissions observed. This data follows the trend shown in Figure 50 where 190 proof ethanol dual fuel tests showed the highest post catalyst NMHC emissions of all dual fuels tests.

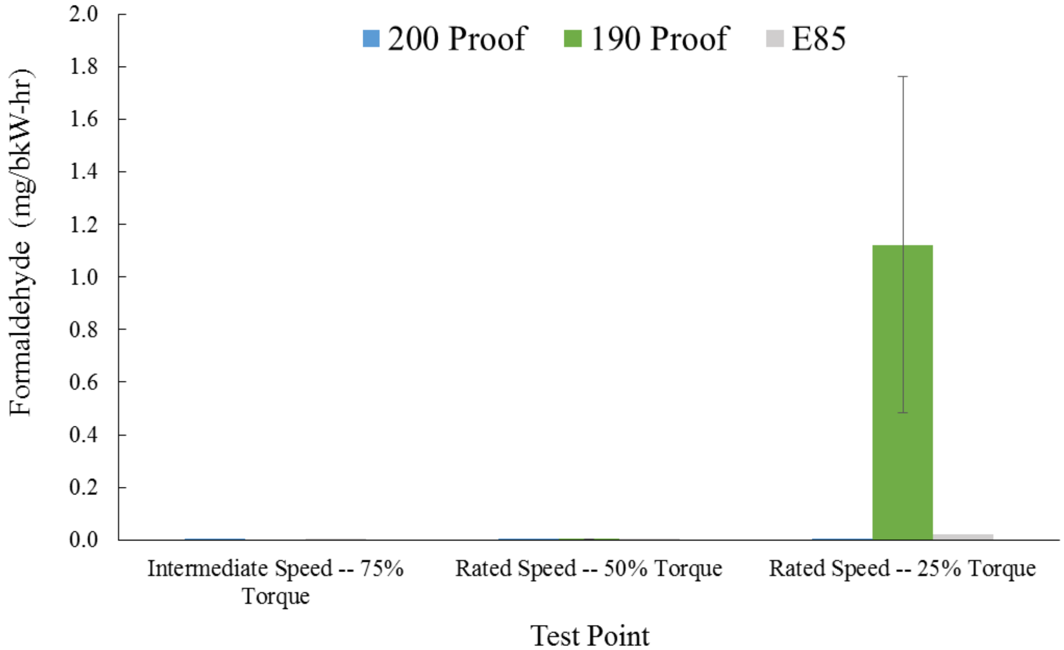

Figure 53. Formaldehyde emissions sampled post catalyst at varied engine speed and torque.

5.3 ENGINE EFFICIENCY AND EXHAUST TEMPERATURE

Heywood [16] was used as a reference for lower heating value of fuels. Figures 54 and 55 show brake specific efficiency as a function of diesel substitution at intermediate speed – 75% torque and as a function of engine speed and load, respectively. Diesel brake specific efficiency was calculated using Equation 7, and at intermediate speed -75% torque was on average 36.3% across all repeated diesel only tests.

$$\eta_b = \frac{W_b}{\sum(m_f Q_{LHV})} \tag{7}$$

Where

W_b = work available at the engine crankshaft

m_f = mass flow rate of fuel

Q_{LHV} = lower heating value of fuel.

The introduction of ethanol based dual fuels increased efficiency by an average of 0.8% at 12% diesel substitution and 3.2% at maximum diesel substitution. This increase in efficiency can be explained by examining dual fuel pressure traces found in Figure 33. During dual fuel tests the engine ECU was allowed to manage parameters such as EGR flow, turbo speed, and diesel exhaust fluid injection rate. When dual fuel tests were conducted the ECU reduced diesel injection to compensate for dual fuel addition. The ECU maps turbo speed to diesel fuel injection and power demand so as the power demand went down the turbo speed also went down. Thus, the motored pressure in the cylinder also went down. This is apparent in Figure 33, presented earlier, where it can be observed that the peak motored pressure using ethanol premixed combustion is reduced by approximately 1500 kPa. This reduction in motored pressure represents less work done by the engine during the compression stage. Despite a lower motored pressure, ethanol premixed combustion traces reach similar peak pressures and follow the diesel combustion trace closely as the combustion process continues into the expanding cylinder volume.

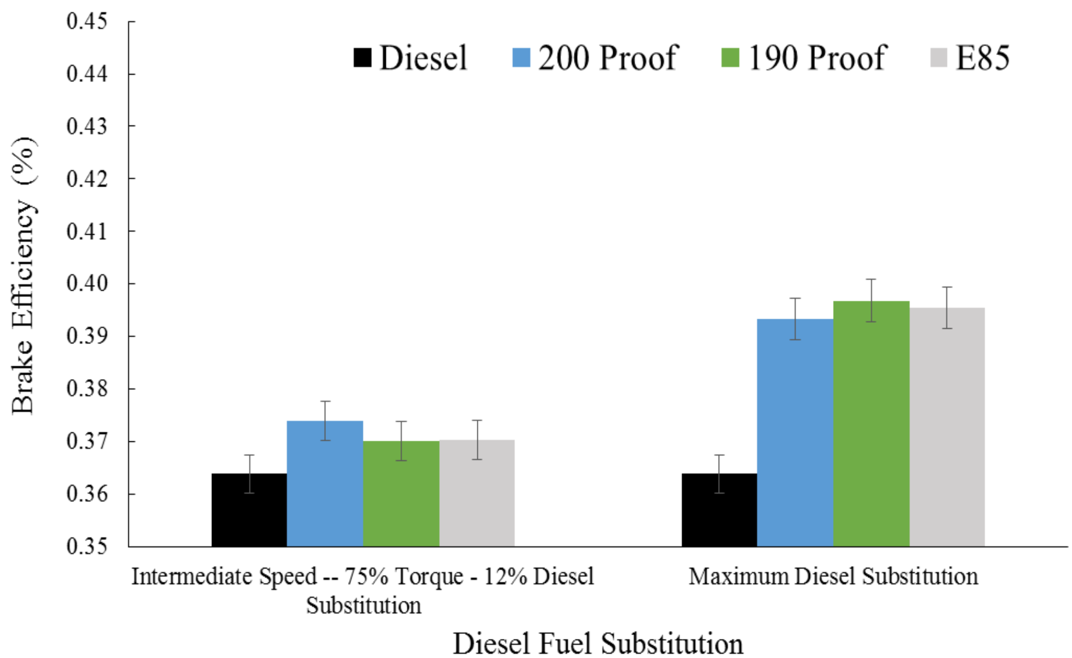

Figure 54. Brake specific engine efficiency at intermediate speed – 75% torque while increasing diesel substitution. Maximum diesel substitution was approximately 25% for all dual fuels.

It should also be noted that the ethanol premixed combustion event occurs almost exclusively after top dead center, which also leads to increased brake specific efficiency. Figure 55 compares diesel combustion efficiency to dual fuel efficiency across the range of test points taken. At rated speed – 50% torque ethanol premixed combustion increases brake specific efficiency by an average of 3.0%. The combustion traces at this speed and load can again be referenced to explain this increase in efficiency. Figure 34, presented earlier, shows the lower dual fuel motored pressure and the ethanol premixed combustion event occurring after top dead center. At rated speed – 25% torque dual fuel efficiency is decreased by 1.4% using 200 proof ethanol and approximately 2% using 190 proof ethanol and E85 fuels. This decrease can be attributed to the lack of ethanol premixed combustion at this lower engine load. Figure 35 confirms this as there is no distinct ethanol premixed combustion event.

A significant reduction in exhaust manifold temperature was observed during dual fuel test points. Figure 56 and 57 show exhaust manifold temperature at varied diesel substitution rates and varied engine

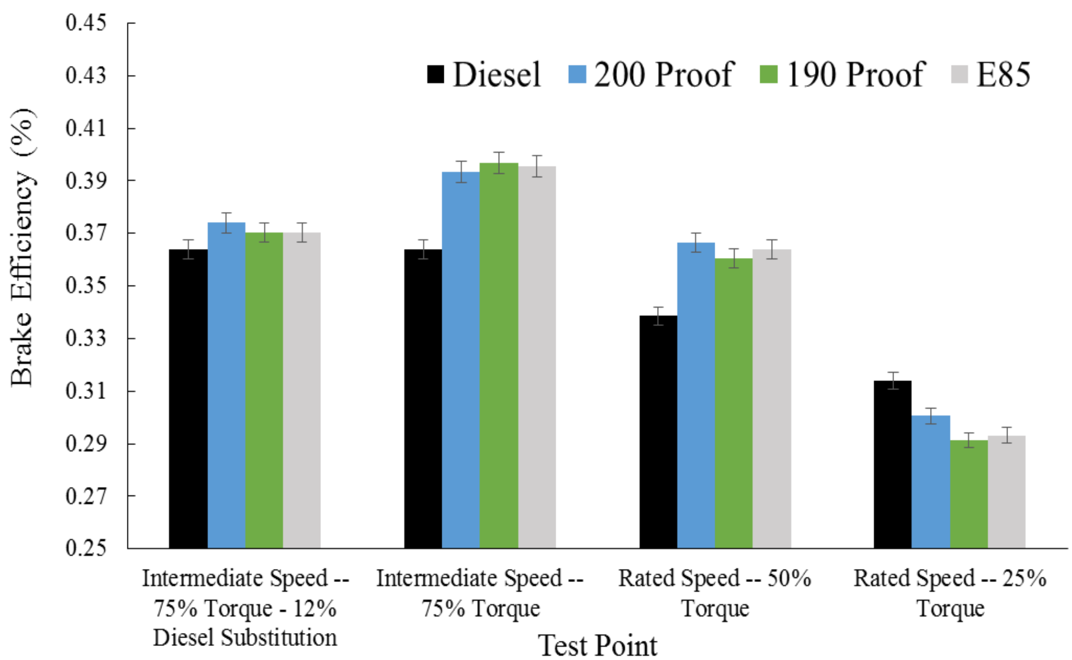

Figure 55. Brake specific efficiency as a function of engine speed and torque. Dual fuel efficiencies represent maximum diesel substitution.

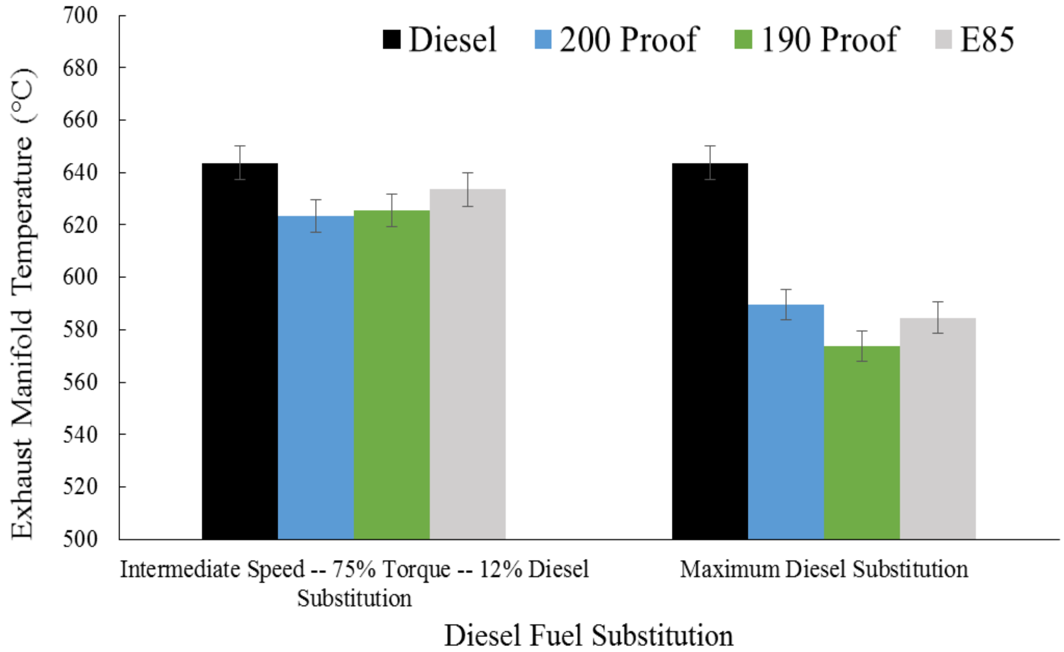

Figure 56. Exhaust manifold temperature as a function of dual fuel type and diesel substitution rate. This data was taken while the engine was operating at intermediate speed – 75% torque.

speed and torque. The largest drop in exhaust temperature occurred at intermediate speed – 75% torque when a 61°C drop in average dual fuel exhaust manifold temperature was recorded at maximum diesel substitution. Reductions in exhaust manifold temperatures were also recorded at rated speed – 50% torque and rated speed – 25% torque where temperature was lowered on average by 41°C and 3°C, respectively.

The after treatment system supplied with the test engine recorded exhaust temperature before and after the DOC and before and after the SCR system using thermistors. These thermistors are used not only to monitor temperature but also to control the activation of NO_x sensors. The thermistors positioned before and after the DOC allowed an analysis of unburned hydrocarbon and CO light off across the oxidation catalyst. Figure 58 shows the change in exhaust temperature across the oxidation catalyst. A negative value signifies a decrease in temperature from inlet to outlet.

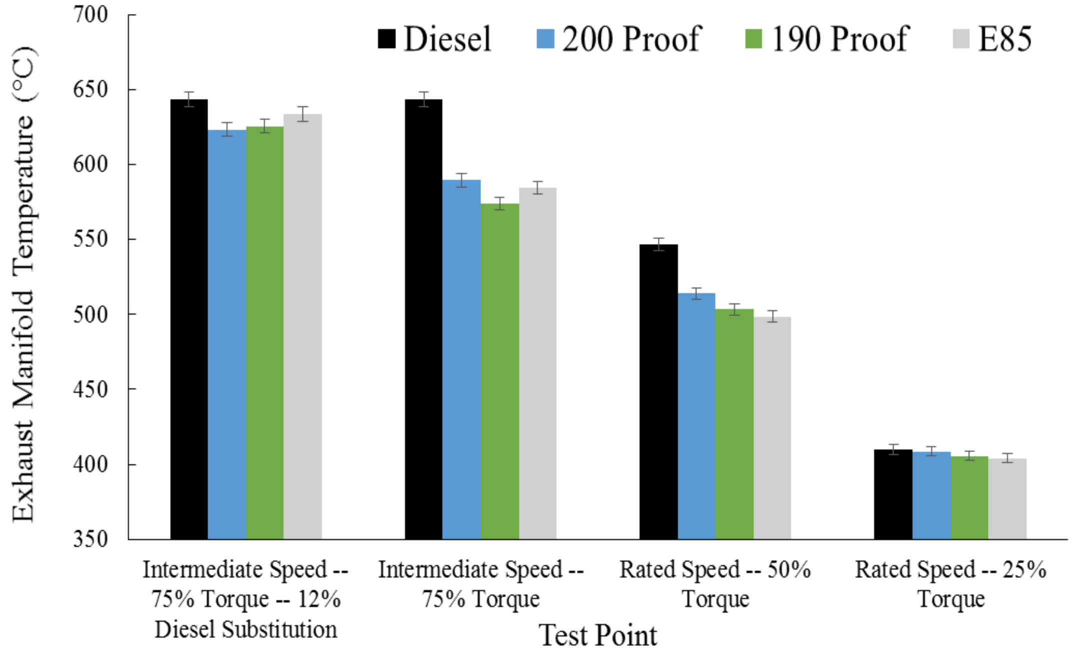

Figure 57. Exhaust manifold temperature as a function of dual fuel type and engine operating point. Dual fuel traces represent maximum diesel substitution points.

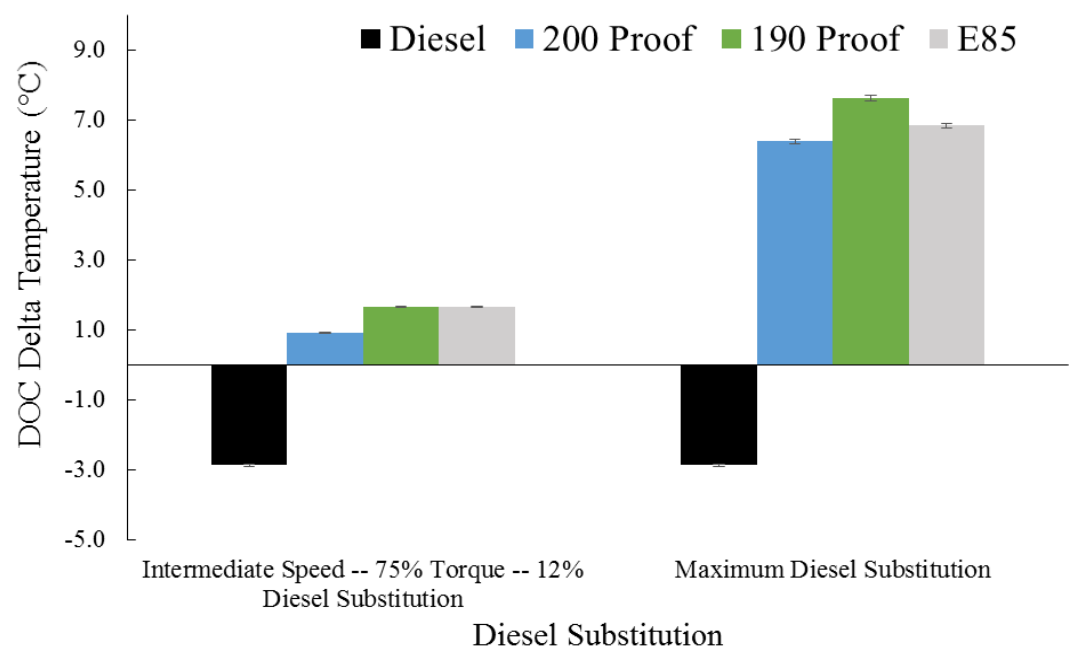

Figure 58. Temperature change across oxidation catalyst at intermediate speed – 75% torque.

At intermediate speed – 75% torque an increase in temperature is observed at all dual fuel test points. This is in contract with the diesel only tests that showed no reaction between the exhaust air and oxidation catalyst and thus a drop in temperature across the catalyst. Figure 59 shows an increase in exhaust temperature change as engine load decreased. 200 proof ethanol dual fuel tests showed a larger temperature increase when compared to 190 proof ethanol and E85 fuel. Diesel fuel baseline data was recorded at rated speed – 50% torque and rated speed – 25% torque, but it can be expected that there would not be any increase in exhaust temperature across the catalyst at these engine test points using only diesel fuel.

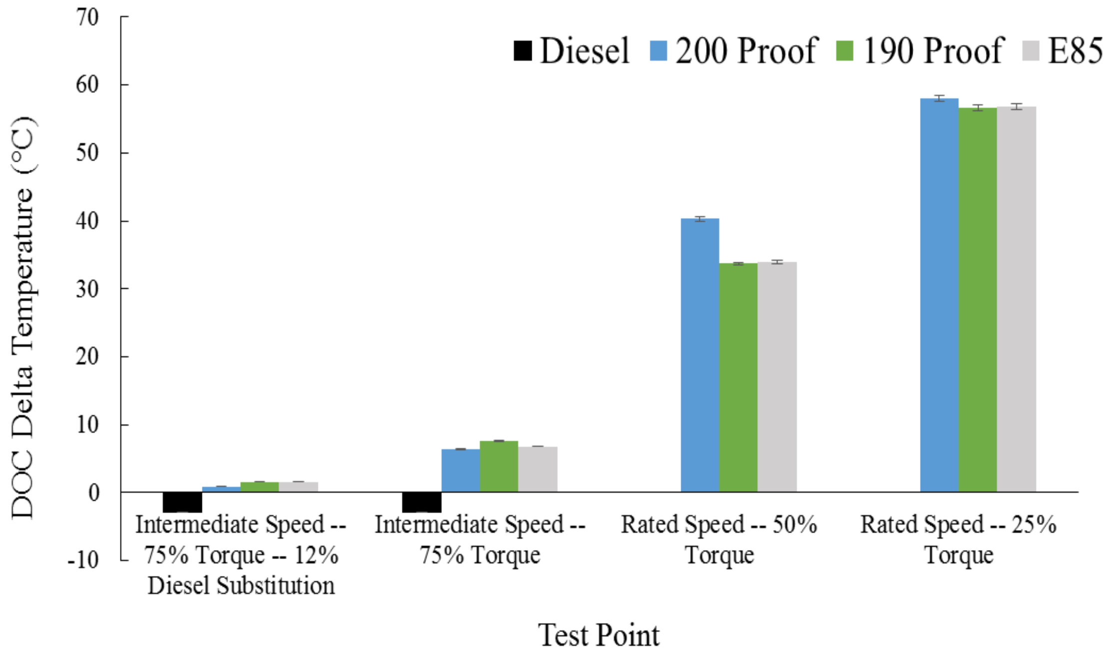

Figure 59. Temperature change across oxidation catalyst at varied engine speed and load. A positive value represents an increase in exhaust temperature across the catalyst. Dual fuel traces represent maximum diesel substitution.

5.4 PARTICULATE MATTER ANALYSIS

Particulate matter data was analyzed and characterized into organic carbon (OC) and elemental carbon (EC) fractions. Total PM was measured by accumulating mass on Teflon filters. This mass contained elemental and organic carbon, but could have also contained other particulates that do belong in either two categories. Total carbon (TC) was measured by accumulating mass on Quartz filters. These filters were heated such that the organic and elemental carbon volatilized off of the filter at different temperatures. Thus, in the following section a distinction between total carbon and total PM is made.

Figure 60 shows how varied diesel substitution and ethanol fuel type effect the ratio of elemental to total carbon. At 12% diesel substitution the ratio of elemental carbon to total carbon increased even when diesel fuel consumption decreased. However, maximizing diesel fuel substitution resulted in lower ratio of elemental to total carbon which was expected due to the tendency of diesel fuel to produce elemental carbon.

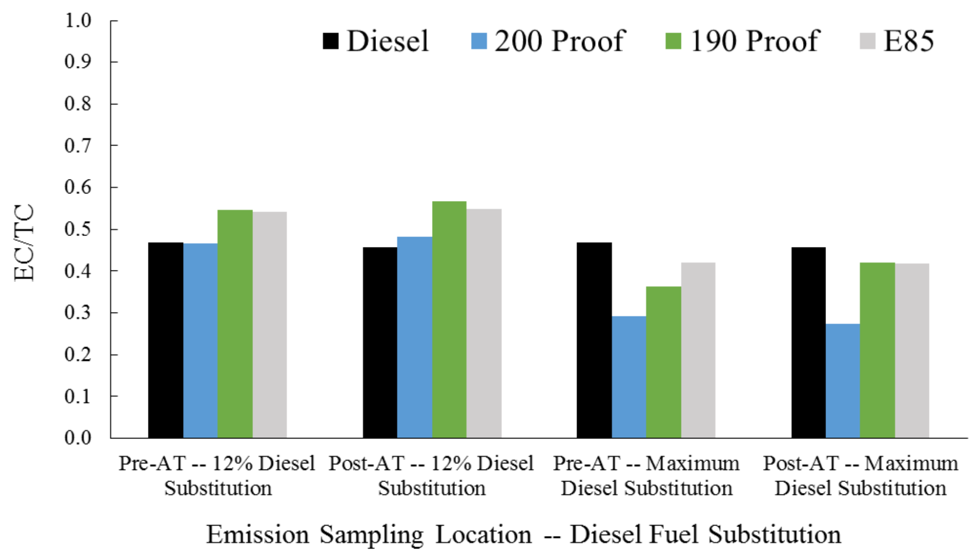

Figure 60. Elemental to total carbon ratio while the engine was operating at intermediate speed – 75% torque

Figure 61 shows EC to TC ratios at different engine speed and torque test conditions. At rated speed – 50% torque the maximum diesel substitution achieved was 43% using 200 proof ethanol. By reducing the diesel consumption by nearly 50% it was expected that the fraction of elemental carbon in exhaust gases would decrease, but conversely this fraction increased when compared to lower diesel substitution tests at intermediate speed – 75% torque and rated speed – 25% torque.

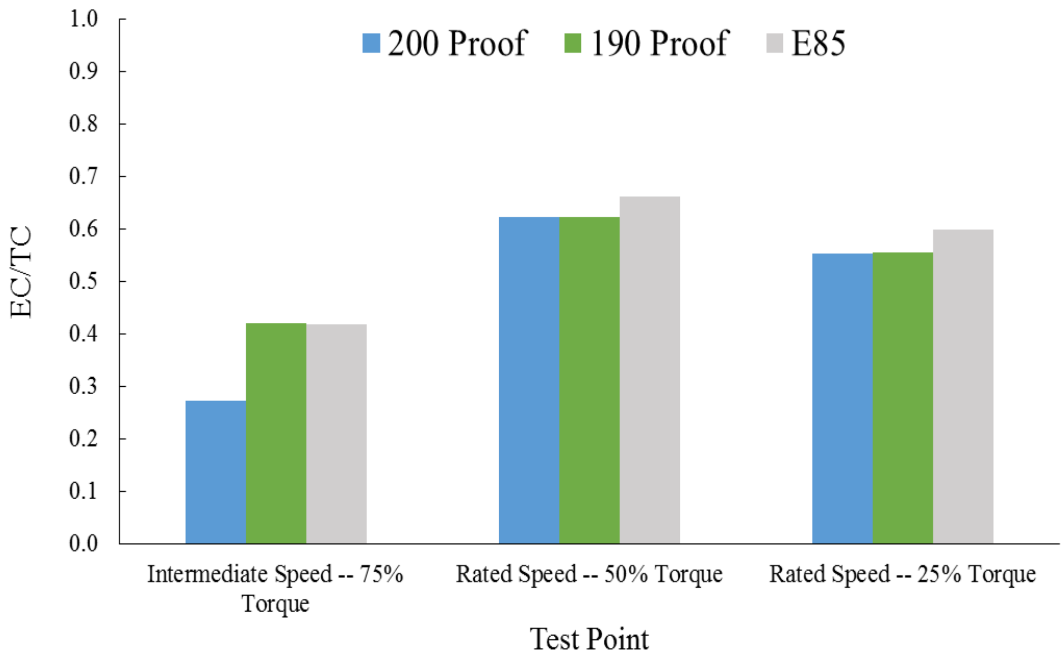

Figure 61. Elemental carbon to total carbon ratio as a function of engine speed and torque. Data represents test points at maximum diesel substitution.

5.5 EMISSIONS DISCUSSION

NO is formed in the high temperature, near stoichiometric regions of burning mixtures in diesel engines [25]. High compression ratios and turbocharged designs enhance NO formation due to an increase in cylinder temperature due to compression of air. Equation 8 shows the initial formation rate for NO as a function of temperature, oxygen, and nitrogen [16].

$$\frac{d[NO]}{dt} = \frac{6 * 10^{16}}{T^{0.5}} \exp\left(-\frac{69090}{T}\right) [O_2]^{0.5} [N_2] \tag{8}$$

The dependence of NO formation on temperature is clear. Further, at typical combustion temperatures NO_2/NO ratios should be small. This theory was supported by this work in which the pre aftertreatment emissions at intermediate speed and 75% torque showed an average NO_2/NO ratio of 0.016 with negligible difference between diesel and dual fuel combustion. Engine operational parameters can also have an effect on NO_x formation, engine out, and post aftertreatment concentrations. Advancing injection timing such that combustion occurs earlier and partially before TDC increases cylinder pressure and thus cylinder temperature which leads to higher concentrations of NO. Conversely, retarding timing lowers peak cylinder pressure and temperature resulting in lower NO formation [16]. Exhaust gas recirculation systems are designed to further reduce maximum combustion temperatures by adding diluent and increasing the charge heat capacity. Finally, urea injection and catalyst size have a significant impact on NO_x reduction in modern diesel engines. Tables 16, 17, and 18 include injection timing, exhaust gas recirculation percentage, maximum cylinder temperature, and urea flow for the three test points and three test fuels.

Table 16. NO_x formation / mitigation operational parameters at intermediate speed – 75% torque.

	Diesel	200 Proof Ethanol 12% Substution	200 Proof Ethanol Maximum Substitution	190 Proof Ethanol 12% Substution	190 Proof Ethanol Maximum Substitution	E85 12% Substution	E85 Maximum Substitution
Diesel Injection Timing (°BTDC)	1.8	-0.2	-0.6	0.2	-0.1	0.2	0.2
EGR (% of total flow)	17.4	19.4	14.5	19.3	14.3	19.4	16.0
Max Cylinder Temperature (K)	1782	1738	1871	1737	1835	1751	1840
DEF Dosing Rate (g/hr)	905.1	569.0	1182.1	554.4	1140.7	560.8	1093.3

Diesel injection timing, EGR, and DEF dosing rate were controlled by the ECU during these tests based on manufacture programming for 100% diesel operation. This information can be used to explain NOx data presented in Figure 42. At each dual fuel 12% diesel substitution test point the EGR percent of total exhaust flow values were higher and the maximum cylinder temperature values were lower, which can explain the lower NO_x emissions at these points. Conversely, at maximum diesel substitution EGR percent of total exhaust flow values were lower and maximum cylinder temperatures were higher than that of diesel fuel which corresponds to the higher engine out NO_x emissions using ethanol dual fuels. In addition the amount of diesel exhaust fluid required to lower these emissions below the Tier 4 Final limit is presented. The maximum diesel substitution tests at intermediate speed and 75% torque

Table 17. NO_x formation / mitigation operational parameters at rated speed – 50% torque.

	Diesel	200 Proof Ethanol	190 Proof Ethanol Maximum	E85 Maximum Substitution
Diesel Injection Timing (°BTDC)	2.7	0.8	0.4	0.7
EGR (% of total flow)	17.4	20.9	20.0	21.7
Max Cylinder Temperature (K)	1547	1583	1546	1570
DEF Dosing Rate (g/hr)		377.3	388.1	412.0

required twice as much diesel exhaust fluid to mitigate NOx emissions. At each test point diesel fuel injection was retarded which would, in standard diesel combustion, lead to lower in cylinder temperatures. However, because there was a clear dual fuel combustion event occurring very close to TDC the NOx reduction effect of retarded injection timing was less evident. Table 17 shows NOx reduction operational parameters at rated speed – 50% torque. Figure 48 shows pre and post aftertreatment NOx emissions at rated speed – 50% torque. Dual fuel, engine out NOx emissions benefitted from increased EGR rates while maximum cylinder temperature increased when using 200 proof ethanol and E85 as dual fuels. Thus, the decrease in engine out NOx at this test point can be explained by increased EGR rates. The reduction in post aftertreatment NOx emissions for dual fuels was not as pronounced as that of diesel fuel operation. This would most likely be due to differing diesel exhaust fluid dosing rates. The diesel baseline diesel exhaust fluid dosing rate data was not collected during this work so a definitive conclusion cannot be given based on the data collected. Table 18 shows operational parameters at rated speed – 25% torque. Similar to the rated speed – 50% test point diesel exhaust fluid dosing rate data was not collected.

Table 18. NO_x formation / mitigation operational parameters at rated speed – 25% torque.

	Diesel	200 Proof Ethanol	190 Proof Ethanol Maximum	E85 Maximum Substitution
Diesel Injection Timing (°BTDC)	1.0	2.5	2.5	2.5
EGR (% of total flow)	19.8	25.4	25.4	25.6
Max Cylinder Temperature (K)	1397	1330	1329	1361
DEF Dosing Rate (g/hr)		255.9	248.9	268.1

At this test point Figure 35 showed that there was no clear dual fuel combustion event, and unburned hydrocarbon emissions limited the diesel fuel substitution. Pre aftertreatment, dual fuel NOx emissions at this test point were lower than that of diesel fuel most likely a result of increased EGR rates and lower maximum combustion temperature. Post aftertreatment, dual fuel NOx emissions did not exhibit the reduction that diesel fuel showed. Pre aftertreatment NOx concentrations at this engine speed and torque were well below concentrations at intermediate speed – 75% torque, and at that point the aftertreatment system was able to reduce emissions far below the Tier 4 limit. Another limiting factor to NOx reduction in an SCR system is exhaust temperature. A difference in exhaust temperature can affect the performance of the NOx reduction catalyst, but Figure 57 shows that the exhaust temperature at rated speed – 25% torque of diesel fuel combustion was nearly identical to that of dual fuel combustion. Thus is can be concluded that the SCR system is sized appropriately and able to reduce the NOx emissions at rated speed – 25% torque. Increased post aftertreatment, dual fuel NOx emissions at this speed and torque can be explained by a non-optimized diesel fluid dosing rate. In addition to NOx sensor data, diesel exhaust fluid dosing may be a function on engine speed and torque. This relationship between engine power and dosing would prevent excessive ammonia slip at lower engine power. Further investigation into the engine ECU and the mapped relationship between diesel exhaust fluid dosing at other parameters would be required to conclusively explain the increase in post aftertreatment NOx emissions at rated speed – 25% torque.

Particulate matter emissions form in fuel rich regions of diffusion flames, and that in practice, pre-mixed fuel and air emit negligible particulate matter emissions due to a lean or near stoichiometric air fuel ratio [25]. Oxidation of particulates generated from fuel rich combustion regions predominately takes place within the cylinder if adequate time for oxidation reactions to be completed [25]. As described in previous chapters the carbon oxygen ratio in the cylinder plays a significant role in the formation of particulate matter. According to Heywood [16] particulate matter formation should occur when the C/O ratio in Equation 9 is greater than one.

$$C_m H_n + y O_2 \rightarrow 2_y CO + \frac{n}{2} H_2 + (m - 2y) C_s \tag{9}$$

This equation is useful to describe particulate matter formation at a local level near the flame. , In general a globally fuel rich mixture tends to produce more particulate matter than a lean mixture. Dual fuel combustion phenomena differs substantially when compared to diesel fuel combustion, and a detailed review of this process was outside of the scope of this work. However, it is important to note the following basic differences between the combustion processes. First, as Figure 33 and 34 show, a premixed ethanol and air combustion event occurs prior to the main diesel combustion event. The premixed ethanol and air combustion is likely a lean combustion event since the ethanol and air mixture entering the cylinder is lean. However, the ethanol in the charge displaces air. It can be inferred then that at the onset of diesel combustion there is less available air and more combustion products in the cylinder, which would lead to a more fuel rich diesel combustion event. Second, turbocharger vane angle is calculated as a function of engine operational parameters. The specific parameters are not known, but as diesel fuel consumption is reduced vane angle is adjusted such that charge pressure and flow are reduced during dual fuel operation. These changes further reduce the available oxygen in the combustion process, and increase the global C/O ratio. Third, increases in exhaust gas recirculation rates also have a detrimental effect to engine out emissions due to a portion of the intake air being replaced by non-reactive combustion products. Finally, previously published literature stated that dual fuel particulate matter emissions were reduced due to lower diffusion combustion, and increased pre-mixed lean or stoichiometric combustion of an oxygenated fuel. Table 19 includes charge pressure, oxidation efficiency, and global air fuel ratio for dual fuel combustion at intermediate speed – 75% torque. These parameters can be used to explain trends shown in Figure 46. Air fuel ratio of dual fuel tests at 12% diesel substitution and maximum diesel substitution were similar to that of diesel fuel at nearly every test, but EGR flow at 12% substitution was higher than that of diesel fuel for all dual fuels. This parameter coupled with the lower air-fuel ratio and charge pressure resulted in higher dual fuel pre aftertreatment PM emissions. At this test point and maximum diesel substitution, EGR flow rates were

Table 19. Engine operational parameters while operating at intermediate speed – 75% torque.

	Diesel	200 Proof Ethanol 12% Substution	200 Proof Ethanol Maximum Substitution	190 Proof Ethanol 12% Substution	190 Proof Ethanol Maximum Substitution	E85 12% Substution	E85 Maximum Substitution
Charge Pressure (kPa)	238.2	231.0	204.8	233.2	204.7	232.7	206.4
Total Oxidation Efficiency (%)	83%	95%	96%	91%	96%	93%	97%
EGR (% of total flow)	17.4	19.4	14.5	19.3	14.3	19.4	16.0
Air-Fuel Ratio	19.4	17.8	19.0	18.0	19.1	18.1	19.4

lower than that of diesel fuel and the air fuel ratio was nearly identical to that of diesel fuel. The diesel substitution was also higher at these test point. The change in operational parameters and diesel substitution can be used to explain the pre aftertreatment NOx emissions at intermediate speed – 75% torque. Total oxidation efficiency is included in Table 19 and represents the ability of the oxidation catalyst to reduce emissions of NMHC, CO, and PM. This efficiency is defined as the percentage of NMHC, CO, and PM oxidized across the catalyst. If pre aftertreatment, dual fuel emissions were too high it would be expected that the oxidation efficiency would be lower than that of diesel fuel. However, the data showed that the oxidation catalyst was sized appropriately and was able to oxidize NMHC, CO, and PM. Table 20 and 21 show operational parameters while the engine was running at rated speed – 50% torque and rated speed – 25% torque, respectively. Post aftertreatment PM data was not collected for diesel fuel operation only, but Figure 51 shows that PM emissions at rated speed – 50% torque and rated speed – 25% torque were nearly 0.1 g/bkW-hr higher than PM emissions at intermediate speed – 75% torque. Tables 20 and 21 show dual fuel EGR rates were higher than diesel fuel EGR rates, and dual fuel charge pressure and air-fuel ratio were lower than diesel fuel. Based on the previous analysis these differences would promote higher PM emissions during dual fuel combustion, which is shown clearly in Figure 51. Without the diesel baseline data at these two engine operation points a conclusive statement cannot be made, but it is theorized that the un-optimized dual fuel PM emissions would be higher than that of diesel fuel only operation.

Table 20. Engine operational parameters while operating at rated speed – 50% torque.

	Diesel	200 Proof Ethanol Maximum Substitution	190 Proof Ethanol Maximum Substitution	E85 Maximum Substitution
Charge Pressure (kPa)	251.1	197.7	204.9	206.1
EGR (% of total flow)	17.4	20.9	20.0	21.7
Air-Fuel Ratio	27.0	20.5	21.5	22.3

Table 21. Engine operational parameters while operating at rated speed – 25% torque.

	Diesel	200 Proof Ethanol Maximum Substitution	190 Proof Ethanol Maximum Substitution	E85 Maximum Substitution
Charge Pressure (kPa)	177.4	162.5	165.1	165.3
EGR (% of total flow)	19.8	25.4	25.4	25.6
Air-Fuel Ratio	34.1	26.6	26.6	27.6

CHAPTER 6
CONCLUSIONS AND FUTURE WORK

The purpose of this work was evaluate ethanol use in compression ignition engines by identifying combustion methods by which ethanol could be used, determining which methods would have the highest diesel substitution rates, and understand the impact that ethanol would have on a modern compression ignition engine. Based on work completed at the CSU Advanced Biofuels Lab and previously published research intake air fumigation using ethanol was identified as a feasible combustion method with high diesel substitution. The impact this combustion method has on a modern compression ignition engine was found by implementing this method on a 2015 Cummins QSB 6.7L engine with a Tier 4 Final emissions system.

The major impacts of ethanol premixed combustion on the test engine were as follows:

1) Maximum diesel substitution at intermediate speed – 75% torque and rated speed – 25% torque was about the same whether using 200 proof ethanol, 190 proof ethanol, or E85 fuel. At rated speed – 50% torque diesel maximum diesel substitution was 43%, 37%, and 39% for 200 proof ethanol, 190 proof ethanol, and E85 fuels, respectively. The average maximum diesel substitution was 25%, 39%, and 25% at intermediate speed – 75% torque, rated speed – 50% torque, and rated speed – 25% torque, respectively. At the two higher engine loads diesel substitution was limited by engine knock, but at low load the substitution was limited by emissions requirements.

2) A premixed ethanol combustion event was observable when analyzing in-cylinder combustion traces while the engine was operating at intermediate speed – 75% torque and rated speed – 50% torque.

3) These events can be characterized by their maximum PRR, which varied with engine speed and torque, but was approximately 3-4 times greater than maximum diesel PRR.

4) Premixed ethanol combustion operation resulted in lower boost pressure and similar peak cylinder pressure when compared to diesel only combustion.

5) Brake specific efficiency at maximum diesel fuel substitution did not vary across the type of dual fuel used. Efficiency was increased by 3.2% and 3.0% at intermediate speed – 75% torque and rated speed – 50% torque, respectively, when compared to diesel only combustion, and efficiency decreased by 1.4% at rated speed – 25% torque compared to diesel combustion.

6) At intermediate speed – 75% torque and maximum diesel substitution premixed ethanol combustion pre catalyst emissions of NO_x, CO, and NMHC increased compared to diesel combustion. Premixed ethanol combustion PM emissions decreased using 200 proof ethanol and 190 proof ethanol but increased using E85 as a dual fuel.

7) The Tier 4 Final emission reduction system was able to reduce NO_x, CO, NMHC, and PM below the Tier 4 limit while the engine was operating at intermediate speed – 75% torque and maximum diesel substitution with the exception of PM emissions using 200 proof ethanol as a dual fuel.

8) EGR flow rates had a significant effect on pre catalyst emissions of NO_x and PM. Fluctuations in these flow rates had a greater effect on emissions levels than diesel substitution rates.

9) The emission reduction systems were able to reduce emissions of NO_x and CO below the required limits at rated speed – 50% torque and rated speed – 25% torque while at maximum diesel substitution.

10) Formaldehyde emissions were measured pre catalyst at intermediate speed – 75% torque during all dual fuel tests and diesel only tests. These emissions were reduced to non-detectable levels post catalyst.

11) Exhaust manifold temperature at maximum diesel substitution while the engine was operating at intermediate speed – 75% torque, rated speed – 50% torque, and rated speed – 25% torque were reduced by an average of 61°C , 41°C, and 3°C, respectively.

12) Premixed ethanol combustion exhaust temperature increased across the oxidation catalyst. The highest increase occurred at rated speed – 25% torque where the temperature increased by 58° C.

13) Performance differences between the three ethanol-based fuels were minor. The fuels could be used nearly interchangeably.

6.1 FUTURE WORK

Future work in this research area should focus on optimization of engine parameters specific to an ethanol based fuel and improved mixing of ethanol and intake air. The ability to modify ECU parameters was available during this work, but the scope did not allow optimization of diesel injection timing, EGR flow rates, and VGT position for dual fuel operation. These parameters have a substantial effect on pre catalyst emissions and overall engine performance. Late diesel injeciton could extend the diesel substitution limits at higher engine loads, and could reduce NO_x emissions, allowing for less EGR to be used.

The KI values recorded during engine knock varied widely across cylinders 6, 5, and 3. When knocking occurred it was not observed on all cylinders. Thus, better mixing of fuel and air prior to entry into the cylinder could extend substitution limits.

Finally, after a single ethanol dual fuel is selected the complete ISO 8178 8-mode test cycle could be run to understand diesel substitution limits at the high and low ends of the test map.

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APPENDIX A

ENGINE DIAGRAMS AND SOFTWARE INTERFACES

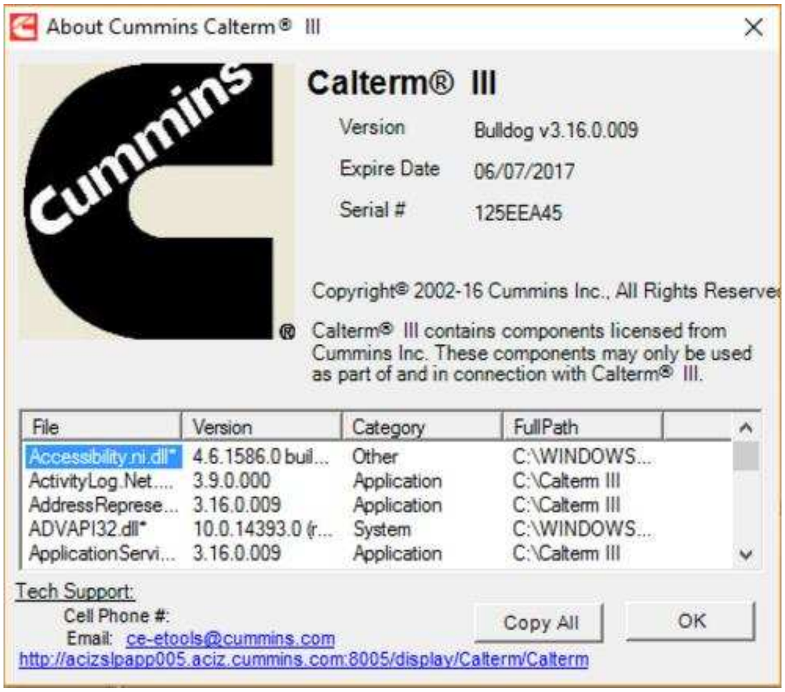


Figure A1. Calterm Version and Serial Number

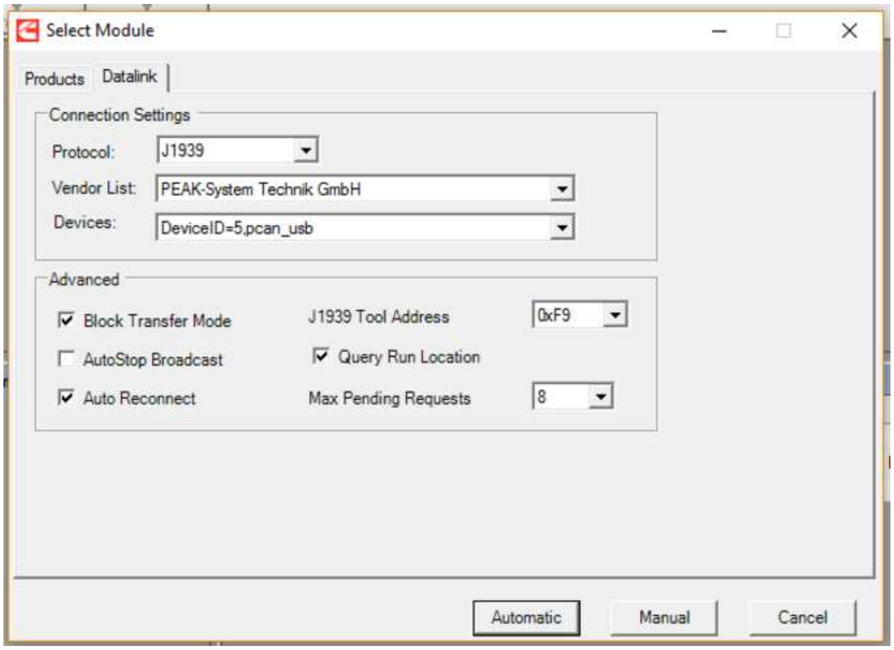


Figure A2. Calterm CAN Network Datalink Settings

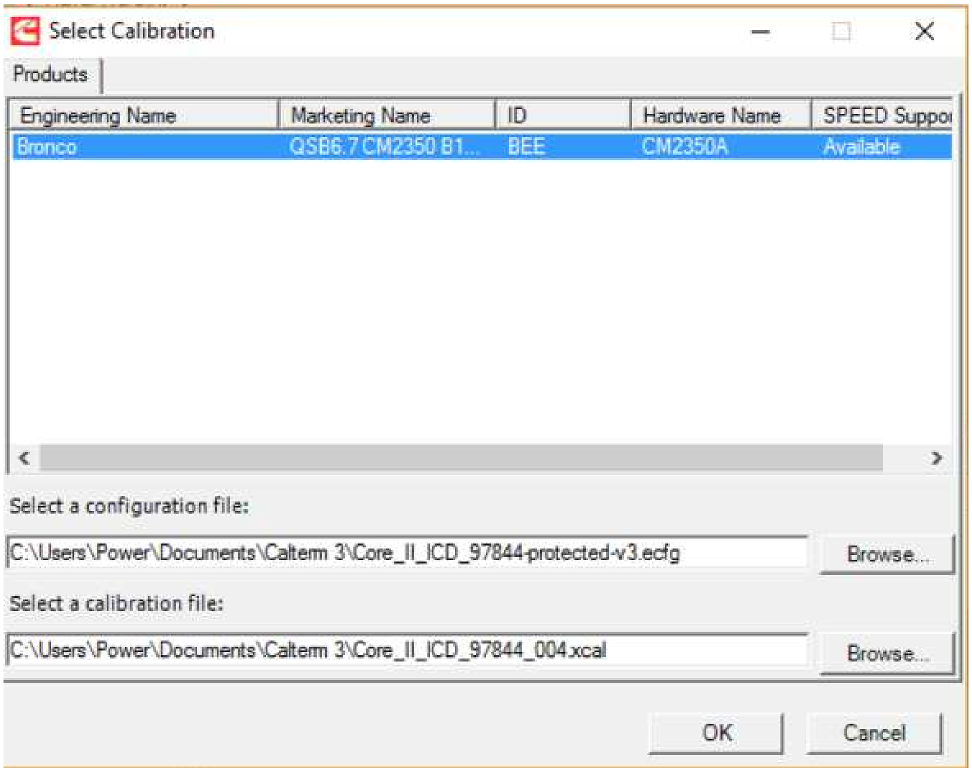


Figure A3. Calterm Configuration and Calibration File Names

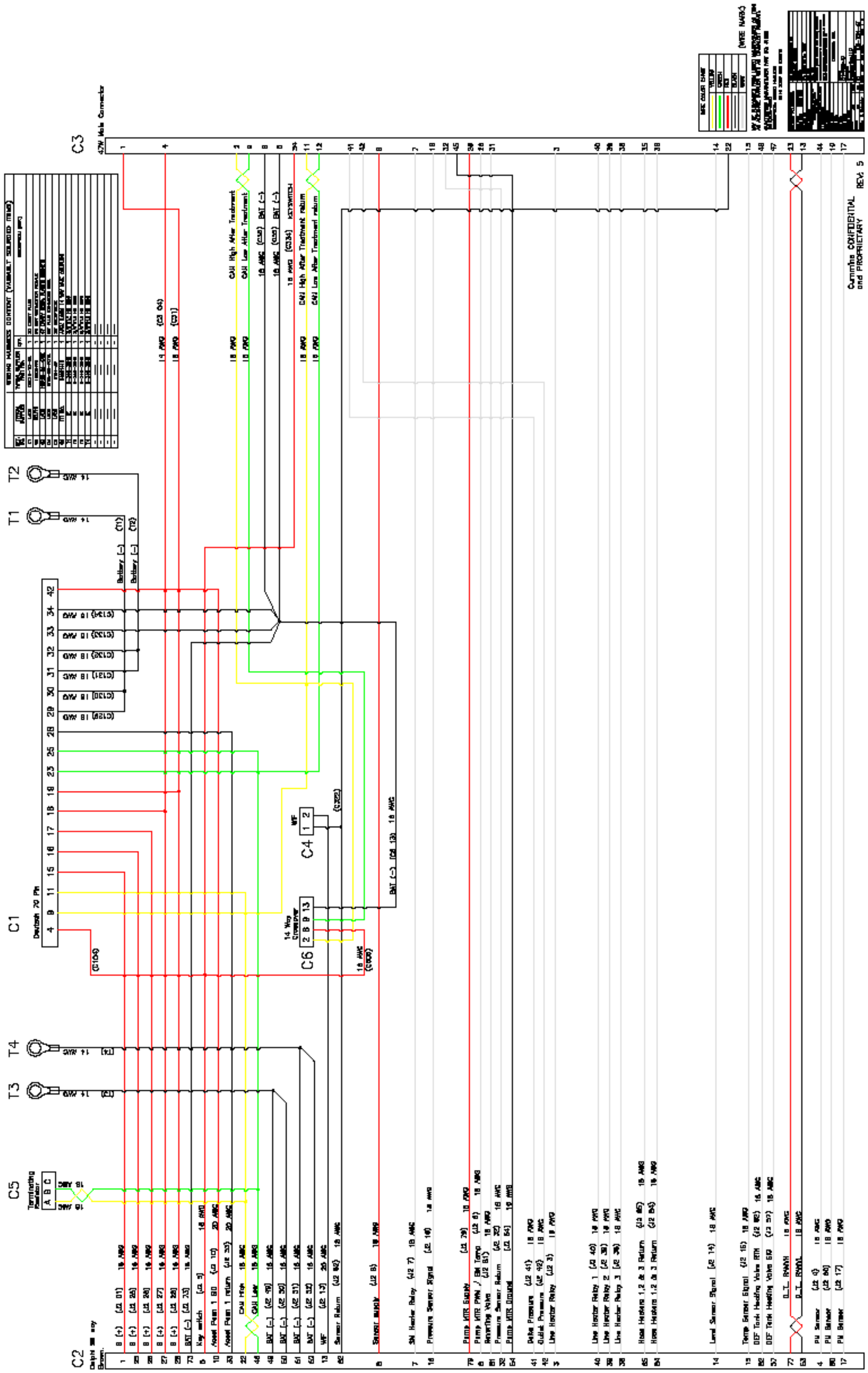


Figure A4. ECU Wiring Diagram 1

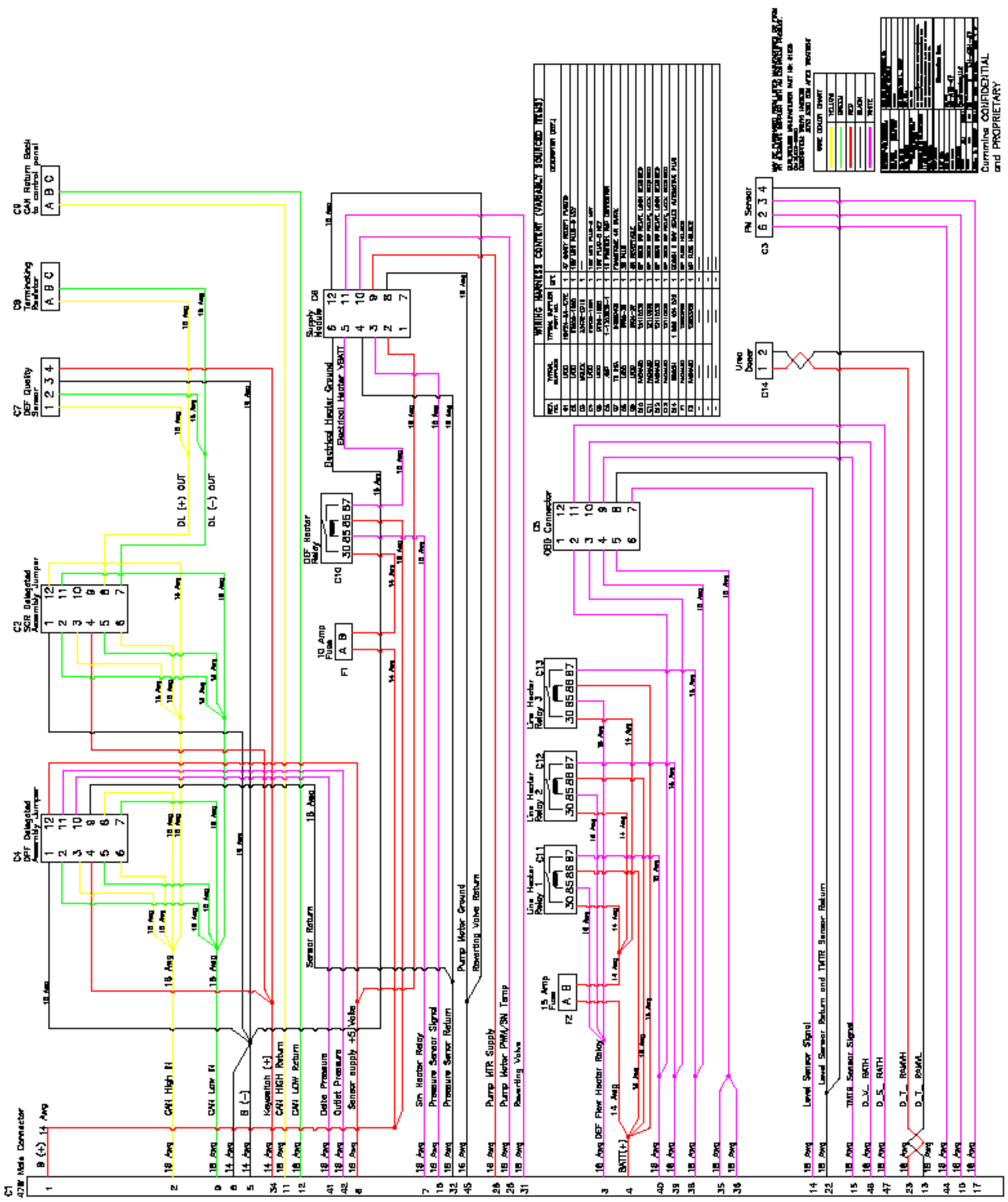
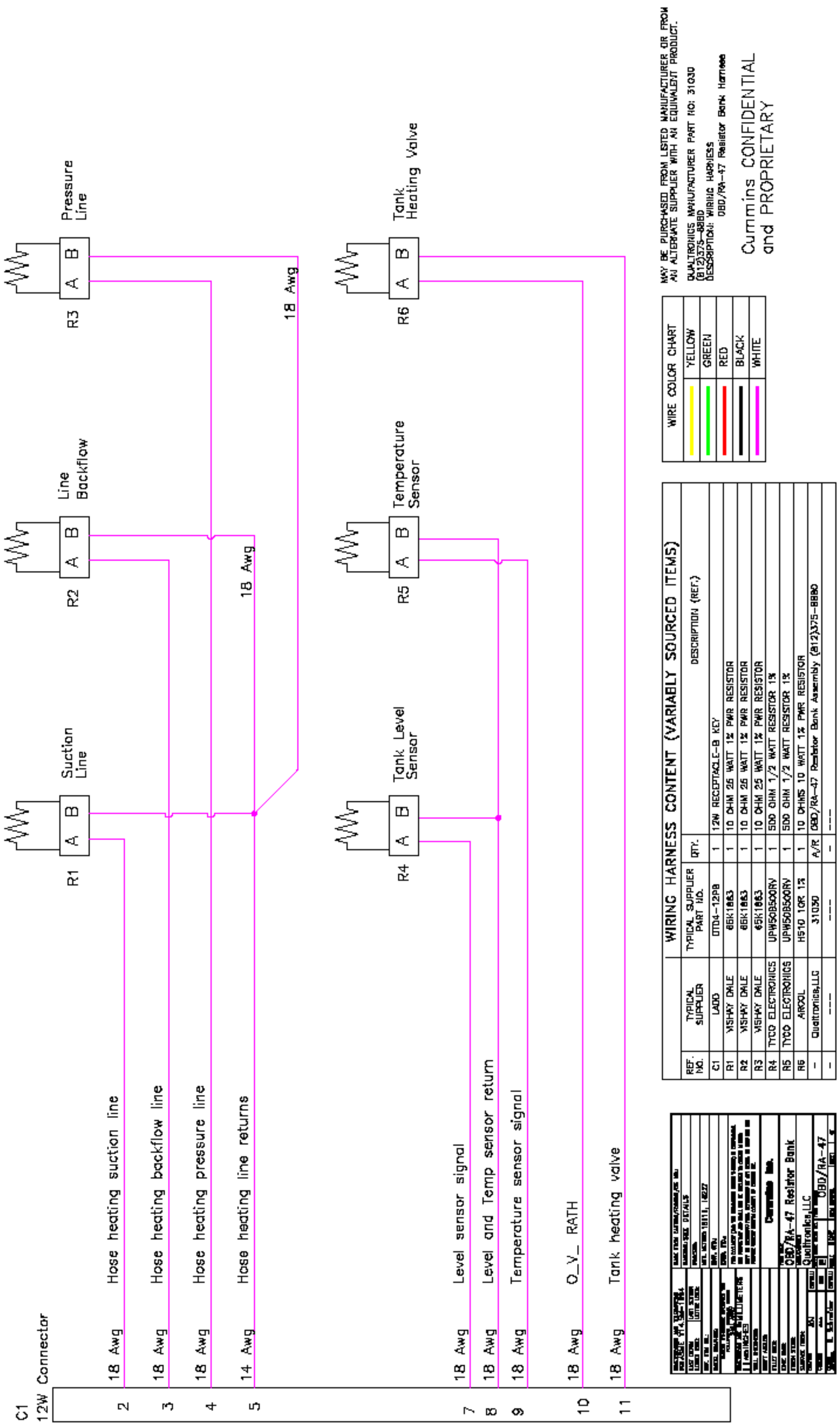


Figure A5. ECU Wiring Diagram 2



a

Figure A6. Wiring Harness Diagram 3

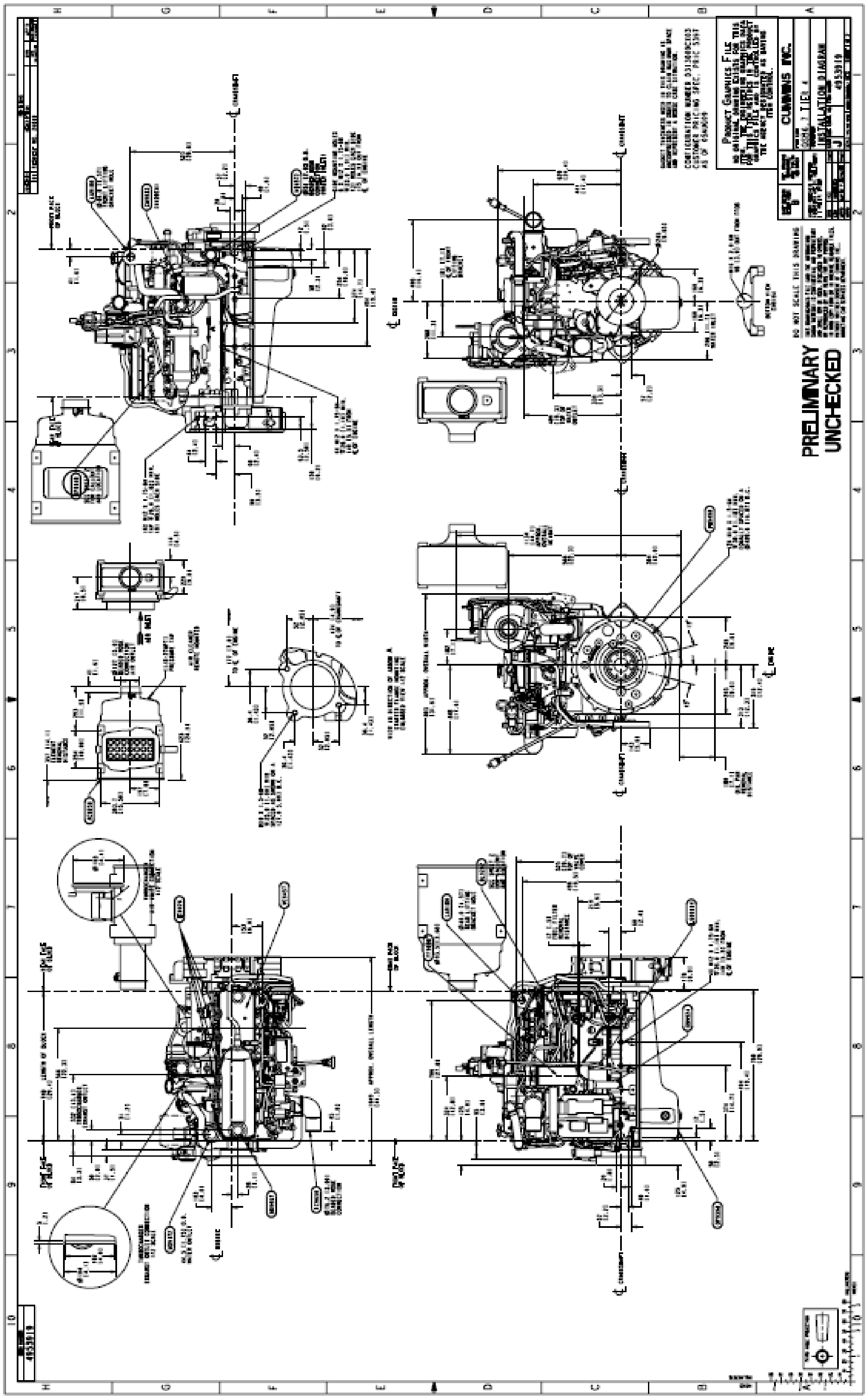


Figure A7. Engine Installation Print

Name	Description
APC_hp_Cmd_cuty	Accumulator pressure command used by the fuel system
APC_hp_Fdbk_cuty	Accumulator Pressure Feedback
APC_i_ImaCmd_cuty	Ima current command
APC_qr_Cmd_cuty	APC flow command
Accelerator_Pedal_Position_cuty	accelerator pedal position [%]
Ambient_Air_Press_cuty	ambient air pressure
Ambient_Air_Tmptr_cuty	ambient air temperature
Battery_Voltage_cuty	battery voltage
CBL_EGR_Frac_Cmd_cuty	EGR fraction command passed to Charge Manger from Combustion Manger Base
CBL_Fuel_Cmd_cuty	fuel command after imposing combustion limits
CBL_MCF_Cmd_cuty	charge flow command passed to Charge Manger from Combustion Manger Base
CBM_Indicated_Trq_Cmd_cuty	indicated torque command from engine manager
CBM_Torque_Fuel_cuty	total torque fueling from CBM base
CBP_Air_Fuel_Ratio_cuty	ait-to-fuel ratio
CBR_Alpha_cuty	alpha unless EGR off, high chi, or user override
CBR_MCF_Ref_cuty	mass charge flow reference, unlimited and uncompensated
CBR_Main_Fueling_cuty	main fueling after substraction of the post and pilot fueling
CBR_Main_SOI_cuty	main SOI
CBR_Max_Ind_Trq_Cmd_cuty	indicated torque command limit
CBR_Pilot2_Fuel_Quantity_Final_cuty	final pilot2 quantity
CBR_Pilot2_SOI_cuty	pilot 2 SOI
CBR_Post1_Fuel_Quantity_Final_cuty	final post 1 quantity
CBR_Post1_SOI_cuty	post 1 SOI
CBR_Post2_Fuel_Quantity_Final_cuty	final post 2 quantity
CBR_Post2_SOI_cuty	post 2 SOI
CBR_Post3_Fuel_Quantity_Final_cuty	final post 3 quantity
CBR_Post4_Fuel_Quantity_Final_cuty	final post 4 quantity
CHL_EGR_Frac_Cmd_cuty	charge manager demanded EGR fraction after limiters
CHL_MCF_Cmd_cuty	charge manager demanded charge flow after limiters
C_CBL_EGR_Frac_Override_Value_cuty	EGR fraction override value before final output to charge reference
C_CBL_MCF_Increment_cuty	mass charge flow incremental value from combustion manager
C_CBL_MCF_Override_Value_cuty	mass charge flow override value before final output to charge reference
C_CBR_Alpha_Chi_cuty	indaicate the chi table that is used as alpha0
C_CBR_Fuelpr_Override_Value_cuty	fuel pressure override value

Figure A8. Calterm Monitored Parameter List

C_CBR_Fuelpr_User_Override_En_cuty	user override enable for fuel pressure
C_CBR_Indc_TrqFuel_Ov_En_cuty	1=use override value; 0-use normally calculated value
C_CBR_Indc_TrqFuel_Ov_Value_cuty	override value for indicated torque fuel from the torque 2 fuel tables
C_CBR_Main_SOI_Override_Val_cuty	main SOI override value
C_CBR_Main_SOI_User_Override_En_cuty	user override enable for main SOI
C_CBR_Pilot2_Fuel_Override_Val_cuty	pilot2 fueling override value
C_CBR_Pilot2_Fuel_User_Override_En_cuty	user override enable for pilot2 fueling
C_CBR_Post1_Fuel_Override_Val_cuty	post1 fueling override
C_CBR_Post1_Fuel_User_Override_En_cuty	user override enable for post1 fuel quantity
C_EGA_Cmd_Override_Value_cuty	EGA position cmd user override value
C_IAT_Cmd_Override_Enable_cuty	IAT position command override enable for the IAT valve controller
C_IAT_Cmd_Override_Value_cuty	IAT position cmd user override value
C_VGA_DL_Cmd_Override_Value_cuty	VGT position command override value
C_VGA_DL_Cmd_User_Override_cuty	enable for VGT psotiion override
Charge_Flow_cuty	charge flow virtual sensor value
Charge_Press_Est_cuty	estimated charge pressure
Charge_Press_cuty	value of charge pressure
Charge_Tmptr_cuty	intake manifold tempearture sensor raw value linerized and filtered
Combustion_Control_Path_Owner_cuty	indicate the ID of "owner" of the current final selected combustion command
Compressor_Inlet_Density_cuty	current density of air at compressor inlet [kg/m3]
Compressor_Inlet_Press_cuty	compressor inlet pressure
Compressor_Inlet_Tmptr_Sensor_cuty	compressor inlet temperature linearized and filtered sensor value
Compressor_Inlet_Tmptr_cuty	compressor inlet temperature measurement of virtual sensor
Compressor_Outlet_Tmptr_cuty	compressor oulet temeprature after all post-processing
Coolant_Temperature_cuty	the linerized and filtered analog value for the fluid engine coolant temperature
Crankcase_Press_cuty	value of crankcase pressure after auto zero
EAC_EGR_Valve_Cmd_cuty	EGR valve position command
ECM_Run_Time_cuty	this data is an integer that counts up or increments every 200 ms
EGR_Delta_Press_cuty	linerized and filtered EGR delta P measurement
EGR_Flow_cuty	EGR flow virtual sensor value
EGR_Fraction_cuty	charge mgr demanded EGR fraction after limiters
EGR_Orifice_Tmptr_cuty	EGR orifice temeprature
EGR_Position_cuty	EGR position raw value linerized
Engine_Speed_cuty	engine speed
Exhaust_Flow_cuty	exhaust flow rate

Figure A9. Calterm Monitored Parameter List

Exhaust_Metal_Tmptr_cuty	exhaust metal temeprature virtual sensor value
Exhaust_Press_cuty	echaust pressure
FSI_q_TotalFueling_cuty	floating point version of total fueling
Filtered_Turbo_Speed_cuty	turbo speed after filtering
Final_Timing_cuty	main timing advance, value equal to CBR_Main_SOI
Fresh_Air_Flow_cuty	fresh air flow virtue sensor value
Friction_Torque_cuty	engine friction torque at current speed and normal engine temperature
Fuel_Delivery_Rate_Per_Min_cuty	mass flow rate of burned fuel as determined for use in A/F ratio calcualtion
IAT_Position_cuty	position of intake air throttle
J39_VGT_Actuator_Position_cuty	VGT actuator actual position
J39_VGT_Target_Position_cuty	VGT actuator target position
J39_VGT_Temperature_cuty	actuator internal temperature
Mach_Control_Path_Owner_cuty	this value indicates the ID of the ower of the current reference being controlled by the machine manager
Mach_Engine_Demand_Torque_cuty	engine demand torque request from machine manger
Net_Engine_Torque_cuty	actual engine torque availible to run all machine loads
OFC_Equiv_Ratio_Limit_cuty	OFC equivalence ratio table output based on engine speed and fueling
OFC_Fuel_Limit_cuty	upper fuel limit above which oxygen is limited
Oil_Pressure_cuty	linerized and filtered analog oil pressure
PTM_Final_Oper_Mode_cuty	final operating mode by EXM. This corresponds to EXXM_ATM_Oper_Mode_Rqst and has been created for Datalink reporting
STA_Main_SOI_cuty	main SOI adjusted by misfire/stumble preventation
STA_Pilot2_SOI_cuty	pilot 2 SOI after misfire/stuble preventation adjustment
STA_Pilot2_Torque_Fuel_Qty_cuty	desired pilot 2 torque fueling before combining regen fueling and limitation and after misfire/stubmble preventation adjustment
TAHR_VGT_LLim_cuty	current VGT lower limit (full open position)
TAHR_VGT_ULim_cuty	current VGT upper limit (full close position)
TGC_VT_Cmd_cuty	turbocharger position command to actuator controller
T_CBL_EGR_Frac_User_Override_cuty	EGR fraction user override in charge reference
T_CBL_MCF_User_Override_cuty	mass charge flow user override on final output of combustion manager
T_EGA_Cmd_User_Override_cuty	EGR position command override enable for EGR valve controller
Total_Fueling_cuty	desired total fueling
Turbo_Speed_Est_cuty	estimated turbo speed
VGT_Position_cuty	VGT position
EPD_Torque_Derate_Value_id	
H_EPD_SpeedDerateValueId	
C_CIP_Override_Raw	
C_CIP_Override_En	

Figure A10. Calterm Monitored Parameter List

EPD_TorqueDerateClass	
EPD_TorqueDerateValue	
EPD_Max_Derate	
EPD_No_Derate_Torque	
EPD_TrqDrtActive	
_Net_Engine_Torque	
V_ATP_trc_DOC_In	
V_ATP_trc_DOC_Out	
V_ATP_trc_DPF_Out	
V_ATP_trc_SCR_In	
V_ATP_trc_SCR_Out	
J39_AFT_Intake_NOx	
J39_AFT_Intake_Per_O2	
J39_AFT2_Intake_NOx	
J39_AFT2_Intake_Per_O2	
J39_AFT2_Outlet_NOx	
J39_AFT2_Outlet_Per_O2	
O_AIM_pr_DPF_DeltaP_Enable	
O_AIM_prg_DPF_OutP_Enable	
T_ATM_bs_Enbl	
J39_AFT_Outlet_NOx	
T_OFC_Fuel_Limit_User_Override	
C_OFC_Fuel_Limit_Override_Value	
_SCR_Catalyst_Inlet_Temperature	
_SCR_Catalyst_Outlet_Temperature	
J39_AT1_DualEGTS_TC1_Tmp	
J39_AT1_DualEGTS_TC2_Tmp	
J39_AT1_TriEGTS_TC1_Tmp	
J39_AT1_TriEGTS_TC2_Tmp	
J39_AT1_DualEGTS_Volt	
J39_AT1_TriEGTS_Volt	
J39_AFT_Intake_NOx_Volt	
J39_AFT_Outlet_NOx_Volt	
_AFT_DEF_Dosing_Rate	
_Diesel_Exhaust_Fluid_Dosing_Valve_ Commanded_Position	
J39_DEF_Tank_Lvl	
J39_DEF_Tank_Tmptr	
_Coolant_Temperature	

Figure A11. Calterm Monitored Parameter List

Charge_Tmptr	
Exhaust_Metal_Tmptr	
Oil_Temperature	
_Exhaust_Temperature	
EGR_Orifice_Tmptr	
_Ambient_Air_Pressure	
Charge_Press	
_Compressor_Inlet_Pressure	
_Crankcase_Pressure	
EGR_Delta_Press	
Exhaust_Press_Sensor	
Oil_Pressure	
Charge_Press_Est	
Compressor_Outlet_Tmptr	
Compressor_Inlet_Press	
Compressor_Inlet_Tmptr_Sensor	
Compressor_Inlet_Tmptr	

Figure A12. Calterm Monitored Parameter List

APPENDIX B

TEST CELL CONSTRUCTION

Figure B1. Test Cell Area Prior to Installation

Figure B2. Test cell skid bolted into its final location. Supported by the I-beam structure underneath

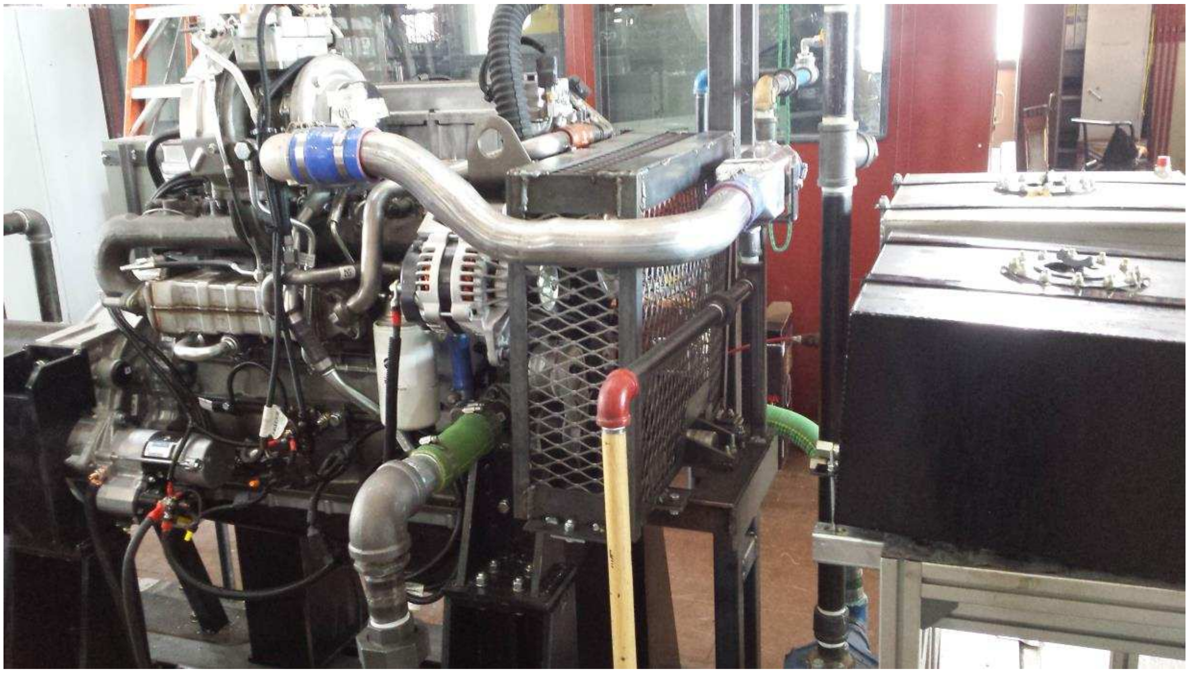


Figure B3. Intake air piping and original fuel tank position.

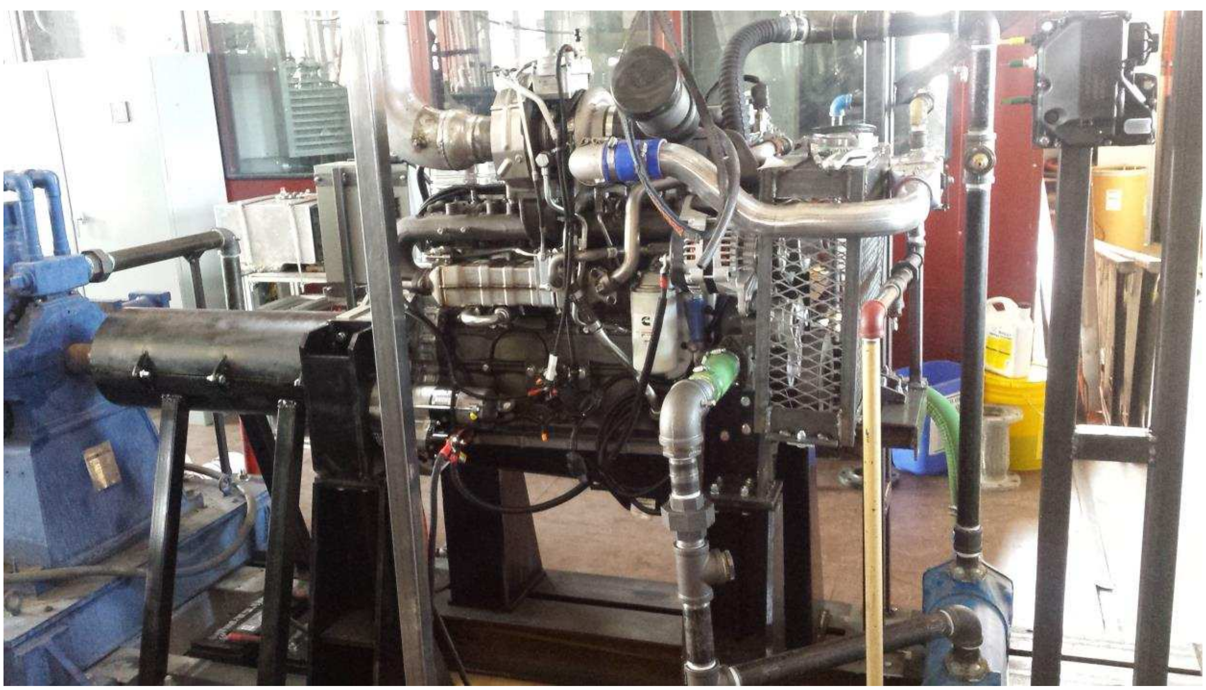


Figure B4. Engine final orientation with coolant plumbing and exhaust partially installed.

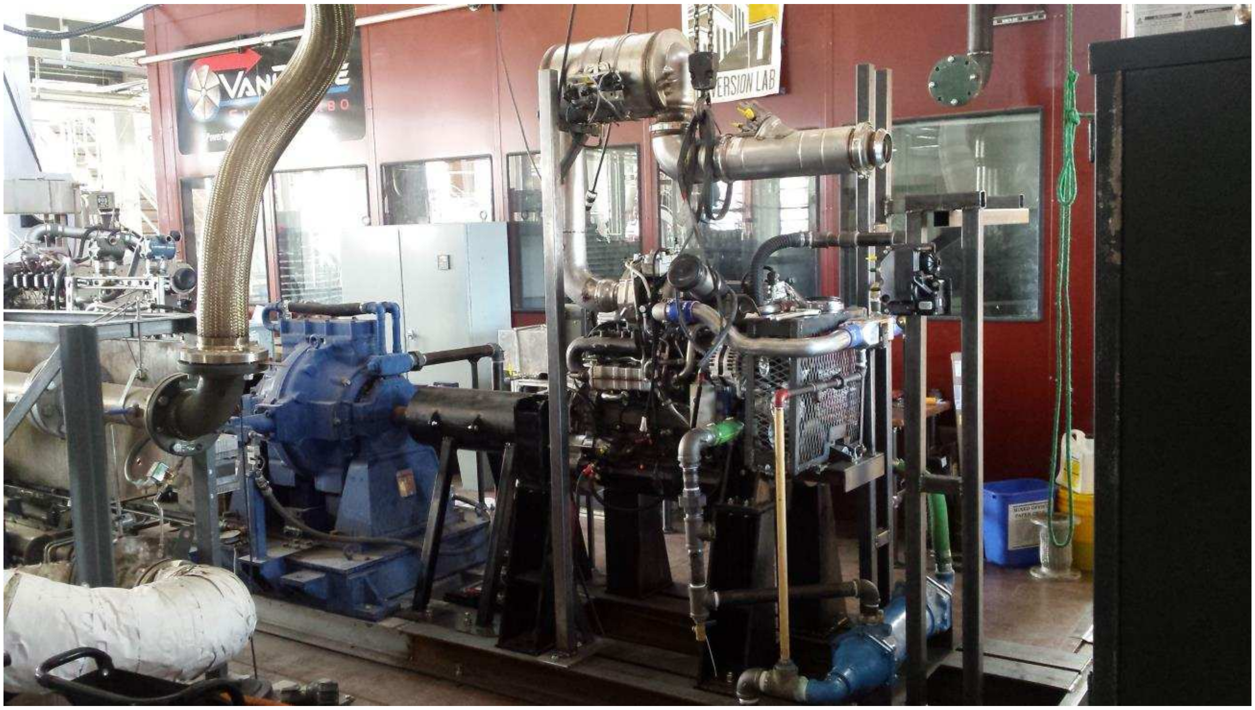


Figure B5. Aftertreatment system installation process.

Figure B6. Final engine test cell.

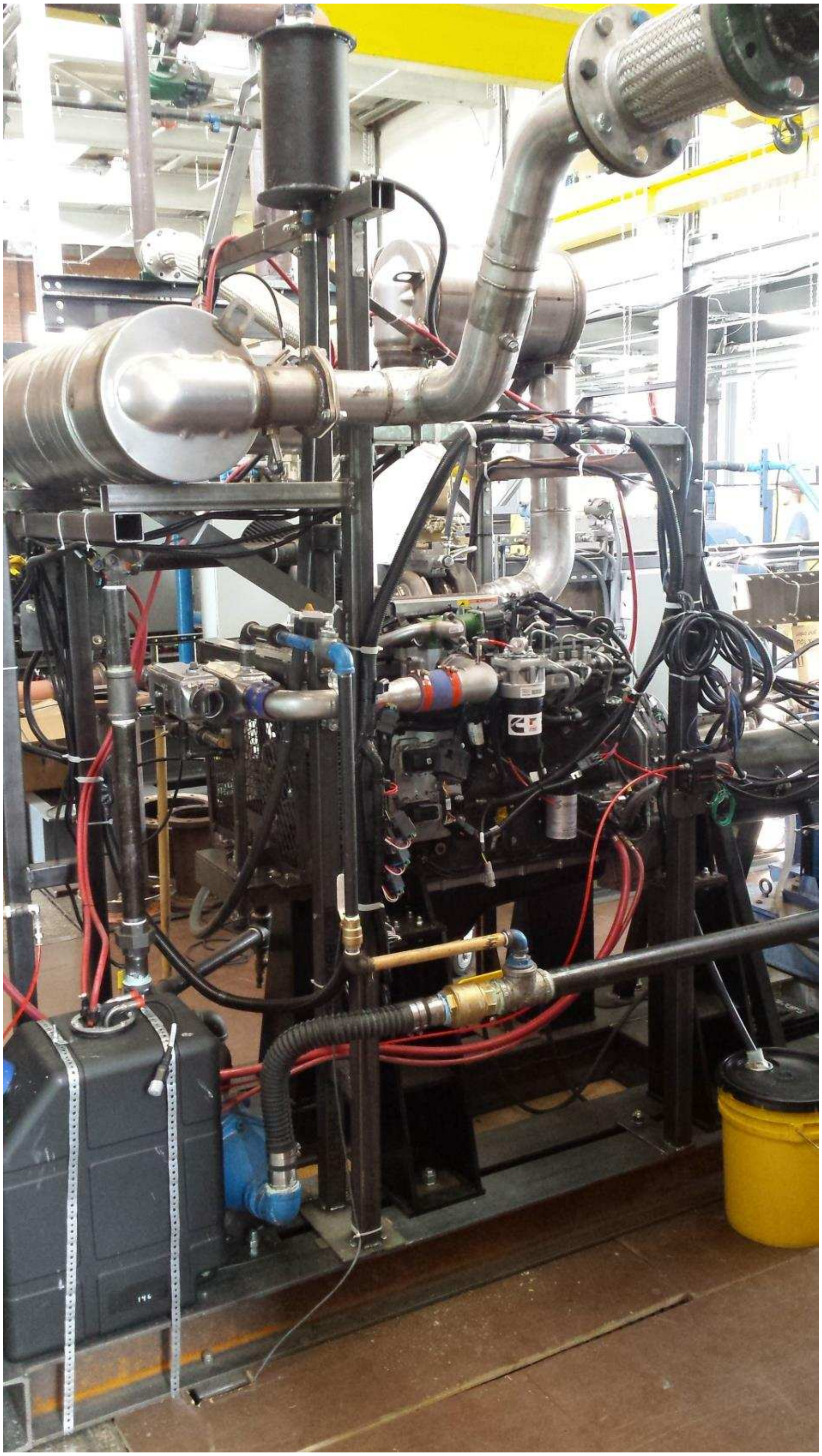


Figure B7. Final engine setup.

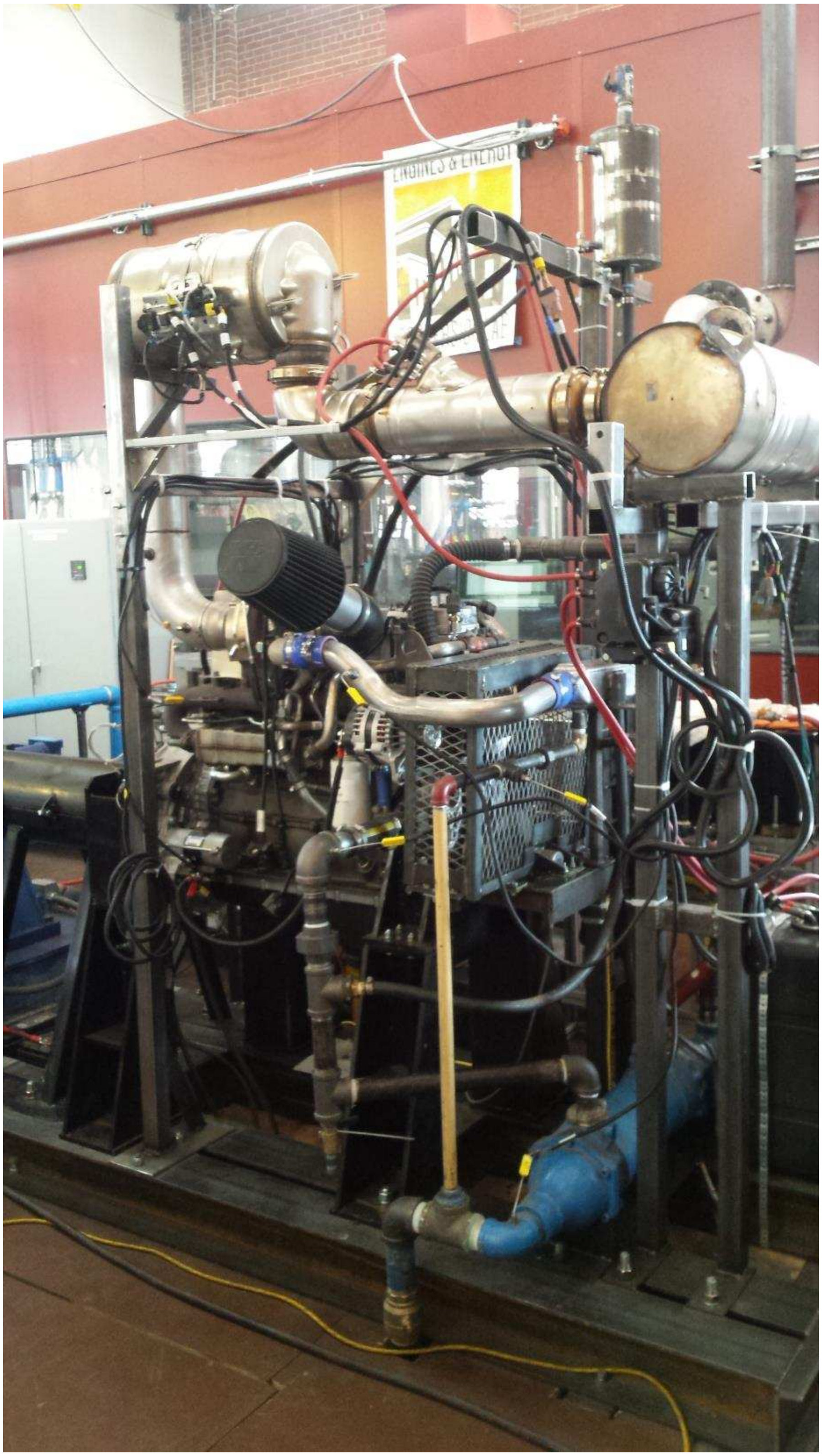


Figure B8. Final engine setup.

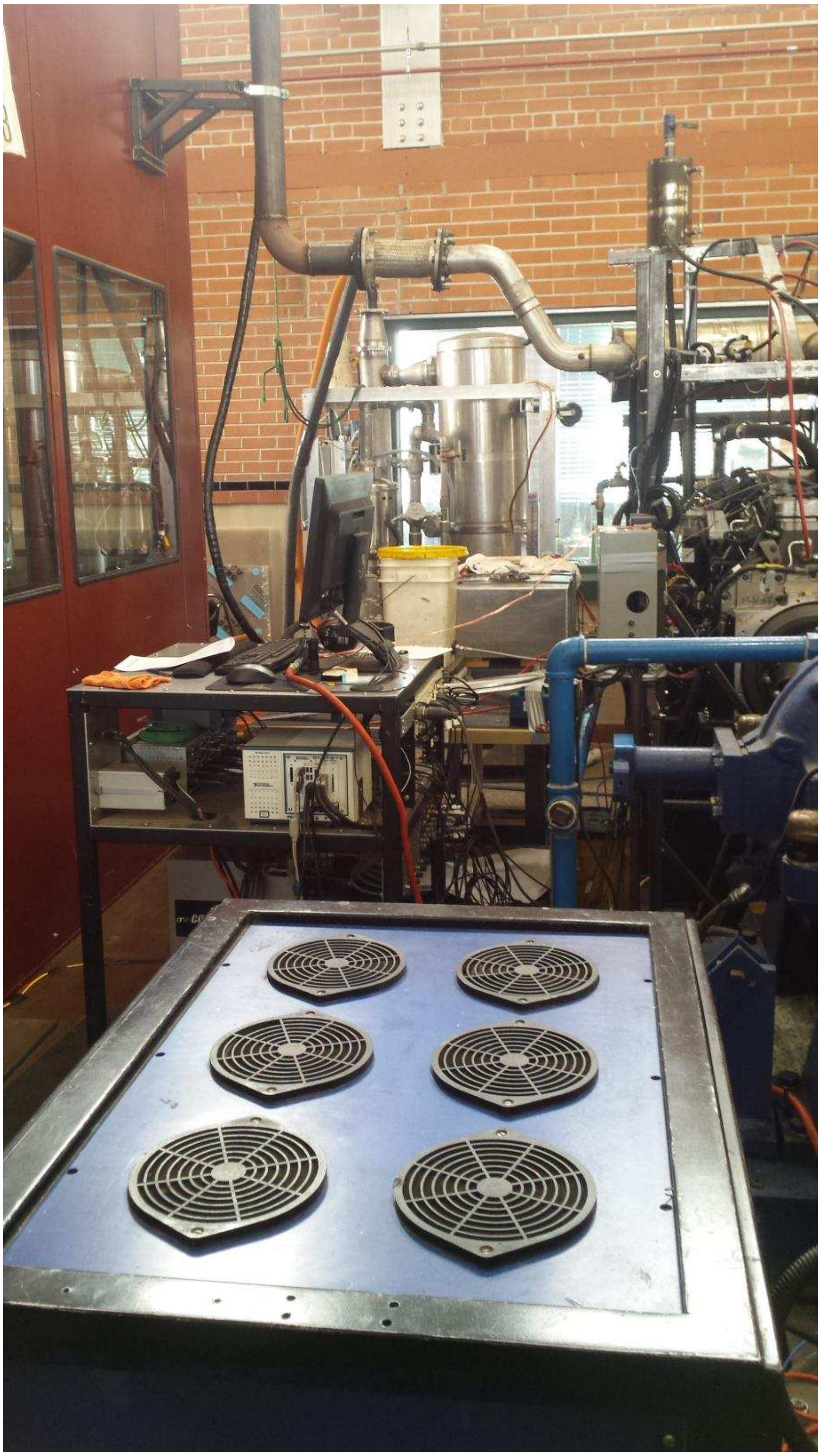


Figure B9. Test day instrumentation setup.

Figure B10. Test day instrumentation setup.

APPENDIX C

CONSOLIDATED RAW DATA

Date Sampled	11/1/2016		11/1/2016		11/1/2016		1/10/2017		1/10/2017		1/10/2017	
Fuel Composition	100% Diesel		100% Diesel		100% Diesel		Diesel - Repeat		DF: 200 Proof		DF: 200 proof	
Engine Speed (rpm)	2456		2455		1807		1817		1811		1810	
Engine Torque (N-m)	250		498		750		751		751		750.6	
Engine Power (kW)	64.29787533		128.0292173		141.9213283		142.8970014		142.4251346		142.2706731	
Test Number	30 - Pre-AT		31 - Pre-AT		32 - Pre-AT		1 - Pre-AT		2 - Pre-AT		3 - Pre-AT	
FTIR (Wet) [PPM]												
Component	Concentration	Std. error	Concentration	Std. error	Concentration	Std. error	Concentration	Std Dev	Concentration	Std Dev	Concentration	Std Dev
Carbon Monoxide high	0	973.80835	0	941.92078	0	758.75409	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Carbon Dioxide	54719.0625	17140.89258	69218.0703	21701.3457	96701.8438	30765.91992	94874.78740	776.12143	95133.95205	764.83906	85318.97814	662.30773
Nitric oxide	265.3629	17.56689	368.7859	22.70203	423.6779	27.89027	381.34711	3.24215	242.82059	5.31542	518.74746	8.55625
Nitrogen dioxide	13.3976	11.48921	9.899	12.73378	9.8291	12.67643	5.84067	1.22683	5.70552	1.57452	6.42914	2.38002
Methane	0.9943	0.45027	0.5494	0.33591	0.4535	0.35021	0.43668	0.14848	1.54837	0.16946	1.37701	0.18773
Methane (Dry)	0.980300719		0.542221654		0.448322743		0.431155986		1.527964868		1.357492672	
Ethylene	0.6287	3.7685	0.4328	4.65351	2.0202	6.31236	1.98559	0.11694	10.81201	0.19070	12.16524	0.15050
Ethane	2.7923	1.89465	1.2054	1.12049	0.1915	0.74977	1.16841	0.20902	0.04144	0.06739	0.02848	0.05272
Propylene	0.63	0.3532	0.5134	0.38208	0.8744	0.4783	0.76082	0.35442	0.20541	0.24519	0.00000	0.00000
Formaldehyde	1.0661	0.0811	0.6961	0.04709	1.8437	0.04122	1.95835	0.09174	13.56082	0.16574	17.70465	0.13084
Formaldehyde (Dry)	1.051089809		0.687004902		1.82265191		1.933580881		13.38214722		17.45375704	
Water	81272.8203	67478.39844	95005.8984	81050.58594	117385.0703	104719.7266	117636.62556	1425.24665	123624.61820	1401.13600	119159.46493	1378.95836
Water (%)	8.12728203		9.50058984		11.73850703		11.76366256		12.36246182		11.91594649	
Propane	8.2036	1.66187	4.2123	0.98282	1.8233	0.65765	2.84154	0.38211	6.82231	1.01176	20.11817	0.22415
Hydrogen cyanide	0	1.34548	0	1.5273	0	1.89048	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Ammonia	0.1023	28.63115	0.0935	35.35484	0	47.95381	0.22790	0.37369	0.19771	0.34337	0.28656	0.40059
Ammonia (Dry)	0.100859664		0.092278348		0		0.225012676		0.195107376		0.282501157	
Carbon Monoxide low	51.9137	2.74895	27.4048	1.53108	34.1035	1.90709	38.21318	0.91136	283.73141	6.09007	403.65306	2.36065
Ethanol							0.00119	0.02070	4.55762	1.16950	16.21378	1.06765
Methanol							18.18827	0.63573	17.87935	0.65828	15.43988	0.76492
NOx	278.7605	0	378.6848	0	433.507	0						
Total Hydrocarbons	30.0606	0	15.2575	0	9.5698	0						
Non Methane Hydrocarb	29.0663	0	14.7081	0	9.1163	0						
VOC's	23.9564	0	12.5022	0	8.7658	0						
5 Gas (Dry)												
THC (ppm)	71.11		55.17		62.68		31.16		102.05		176.78	
THC(%)	0.0071		0.0055		0.0063		0.0031		0.0102		0.0177	
O2 (%)	12.36		10.05		5.10		5.30		5.00		6.66	
NOx (ppm)	311.66		412.79		471.63		342.08		210.25		452.03	
CO2 (%)	6.27		8.03		11.64		10.53		10.67		9.49	
CO2 (ppm)	62696.72		80253.58		116388.85		105312.59		106662.64		94870.40	
CO (ppm)	62.67		38.14		46.66		52.20		296.95		413.39	
CO (%)	0.01		0.00		0.00		0.01		0.03		0.04	
N_2 Value	0.01		0.01		0.01		0.01		0.01		0.01	
NMHC (ppm)	70.12		54.63		62.23		30.73		100.52		175.42	

Figure C1. Raw FTIR and 5-Gas Data

Date Sampled	1/10/2017		1/10/2017		1/10/2017		1/12/2017		1/12/2017		1/12/2017	
Fuel Composition	DF: 200 proof		DF: 200 proof		DF: 200 proof		Diesel - Repeat		DF: 190 proof		DF: 190 proof	
Engine Speed (rpm)	1815		1808		1822		1816		1813		1812	
Engine Torque (N-m)	750.6		751.1		751		751.4		750.5		750.4	
Engine Power (kW)	142.663686		142.2081345		143.2902237		142.8944253		142.4874951		142.3899278	
Test Number	4 - Pre-AT		5 - Post-AT		7 - Post-AT		11 - Pre-AT		12 - Pre-AT		14 - Pre-AT	
FTIR (Wet) [PPM]												
Component	Concentration	Std Dev	Concentration	Std Dev	Concentration	Std Dev	Concentration	Std Dev	Concentration	Std Dev	Concentration	Std Dev
Carbon Monoxide high	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Carbon Dioxide	85915.69634	648.84951	92329.17294	609.94198	84425.64063	641.14096	96482.00978	633.20681	95349.74333	649.79123	85541.69648	685.22499
Nitric oxide	493.90125	7.19756	12.13621	0.38228	12.93429	0.70821	391.80103	3.74857	234.35182	5.61412	509.94615	12.78615
Nitrogen dioxide	6.72813	2.24399	6.67979	1.10285	6.34976	1.01646	5.28427	1.03398	5.55210	1.31825	5.23897	1.45500
Methane	1.47650	0.18367	1.89621	0.13835	2.62500	0.15537	0.38401	0.14387	1.58562	0.16846	1.49471	0.18566
Methane (Dry)	1.45555522		1.871864324		2.588379595		0.379143542		1.564662209		1.473568012	
Ethylene	12.59511	0.15083	0.05953	0.07318	0.06424	0.07202	1.92230	0.10716	10.29447	0.25806	12.26575	0.17550
Ethane	0.00129	0.00937	0.00000	0.00000	0.00088	0.02424	0.35440	0.11894	0.00370	0.01696	0.00738	0.02530
Propylene	0.00000	0.00000	0.33919	0.31058	0.35054	0.30016	0.81467	0.34971	0.20108	0.24737	0.00000	0.00000
Formaldehyde	18.15571	0.12441	0.00008	0.00153	0.00025	0.00429	2.00682	0.07675	13.20397	0.33494	18.10118	0.14926
Formaldehyde (Dry)	17.89820554		7.74244E-05		0.000245222		1.981412059		13.02944399		17.84512076	
Water	119972.16461	1320.17151	120976.57508	1353.73796	119122.82187	1376.57331	119604.40344	1356.13660	124661.42076	1373.51759	120447.98932	1352.72398
Water (%)	11.99721646		12.09765751		11.91228219		11.96044034		12.46614208		12.04479893	
Propane	20.07000	0.19114	0.07205	0.06131	0.08925	0.06136	1.86986	0.18168	6.91260	0.41898	20.81160	0.20174
Hydrogen cyanide	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00126	0.03473
Ammonia	0.25114	0.38297	0.39162	0.45532	0.34017	0.43167	0.35092	0.43394	0.15758	0.30243	0.34912	0.44244
Ammonia (Dry)	0.247575314		0.386593019		0.335424569		0.34647346		0.155498788		0.344184381	
Carbon Monoxide low	411.98865	2.44682	0.17421	0.02848	0.04062	0.02478	39.35589	1.25566	264.16414	10.90623	384.91755	2.95985
Ethanol	16.24390	1.06090	0.00000	0.00000	0.00041	0.01122	0.01713	0.10152	4.55920	0.86252	16.97957	1.04873
Methanol	15.57238	0.77446	16.39919	0.63088	15.09378	0.61523	17.56077	0.60318	17.30648	0.65738	15.43271	0.71711
NOx												
Total Hydrocarbons												
Non Methane Hydrocarb												
VOC's												
5 Gas (Dry)												
THC (ppm)	181.64		11.86		9.94		28.06		99.87		185.58	
THC(%)	0.0182		0.0012		0.0010		0.0028		0.0100		0.0186	
O2 (%)	6.53		4.75		6.26		5.31		5.19		6.75	
NOx (ppm)	426.82		7.87		8.13		415.79		262.93		557.56	
CO2 (%)	9.55		10.72		9.69		10.72		10.74		9.62	
CO2 (ppm)	95514.51		107181.18		96922.76		107223.15		107369.96		96229.48	
CO (ppm)	422.69		3.40		3.45		53.52		273.63		392.16	
CO (%)	0.04		0.00		0.00		0.01		0.03		0.04	
N_2 Value	0.01		0.01		0.01		0.01		0.01		0.01	
NMHC (ppm)	180.18		9.99		7.36		27.69		98.31		184.11	

Figure C2. Raw FTIR and 5-Gas Data

Figure C3. Raw FTIR and 5-Gas Data

Date Sampled	1/12/2017		1/12/2017		1/13/2017		1/13/2017		1/13/2017		1/13/2017		1/13/2017	
Fuel Composition	DF: 200 proof		DF: 200 proof		DF: 190 proof		DF: 190 proof		DF: 190 proof		DF: 190 proof		DF: E85	
Engine Speed (rpm)	2447		2449		1813		1813		2436		2473		1805	
Engine Torque (N-m)	496.8		251.1		751.1		751.1		497.9		251.3		750.6	
Engine Power (kW)	127.3045153		64.39672023		142.6014092		142.6014092		127.0128501		65.07959717		141.8776601	
Test Number	15 - Post-AT		16 - Post-AT		17 - Post-AT		19 - Post-AT		20 - Post-AT		21 - Post-AT		22 - Post-AT	
FTIR (Wet) [PPM]														
Component	Concentration	Std Dev	Concentration	Std Dev	Concentration	Std Dev	Concentration	Std Dev	Concentration	Std Dev	Concentration	Std Dev	Concentration	Std Dev
Carbon Monoxide high	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Carbon Dioxide	73739.26789	475.38791	60910.43101	430.06723	94902.99432	661.66592	85816.07086	597.56154	73186.75910	512.81356	60929.59031	501.76534	96424.81509	714.47675
Nitric oxide	21.39236	0.48825	24.51251	0.44334	3.28597	0.30829	5.23106	0.35129	15.41699	0.56870	24.96256	1.55835	4.29107	0.30442
Nitrogen dioxide	5.33302	0.89195	7.35048	0.66973	5.72973	1.13714	5.46373	1.01440	5.05072	0.83660	7.28579	0.62069	6.62787	1.08013
Methane	26.16703	0.43070	52.71061	0.65417	2.43432	0.15791	2.82518	0.14688	23.60542	0.25402	56.25490	1.07928	2.02551	0.18734
Methane (Dry)	25.74510092		51.83864941		2.401184641		2.783555979		23.22441051		55.29826868		1.998345614	
Ethylene	0.09567	0.08165	0.09656	0.08135	0.09360	0.08536	0.09293	0.08119	0.19525	0.09470	1.35046	0.23919	0.10085	0.08528
Ethane	0.01441	0.03506	0.73518	0.10202	0.22399	0.13948	0.00157	0.01585	0.06648	0.06663	1.44233	0.09643	0.00000	0.00000
Propylene	0.36766	0.30355	0.38775	0.31804	0.33607	0.29513	0.34069	0.30218	0.37444	0.29771	0.38371	0.31453	0.30665	0.29175
Formaldehyde	0.00035	0.00419	0.00017	0.00309	0.00000	0.00000	0.00000	0.00000	0.00014	0.00242	0.12146	0.10135	0.00018	0.00294
Formaldehyde (Dry)	0.000347705		0.000167123		0		0		0.00014147		0.119398516		0.000180788	
Water	115723.24274	1282.30725	98100.32405	1148.01276	125272.99047	1359.64004	122457.40071	1376.43480	114306.02495	1224.82076	100091.38175	1229.21954	125614.02509	1373.47757
Water (%)	11.57232427		9.810032405		12.52729905		12.24574007		11.4306025		10.00913818		12.56140251	
Propane	1.29732	0.07814	2.26090	0.08242	0.72168	0.20221	0.36821	0.07372	2.22651	0.19154	6.10112	0.56197	0.00546	0.01716
Hydrogen cyanide	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Ammonia	0.16177	0.29097	0.18622	0.32427	0.08705	0.22505	0.10884	0.24193	0.10797	0.24914	0.14740	0.29219	0.07517	0.19234
Ammonia (Dry)	0.159158618		0.183141642		0.085870025		0.107231463		0.106231054		0.144892129		0.074162023	
Carbon Monoxide low	0.41815	0.02545	0.35210	0.02755	0.15606	0.02415	0.00760	0.01346	1.19052	0.05078	3.99345	0.39841	0.04903	0.02351
Ethanol	0.06216	0.19536	0.40153	0.48281	0.00144	0.02580	0.00140	0.02388	0.01804	0.10305	0.55216	0.58159	0.00093	0.02569
Methanol	13.52493	0.59852	11.35790	0.58362	16.81056	0.56965	15.37300	0.57690	13.27749	0.59560	11.64668	0.58462	16.92039	0.62151
NOx														
Total Hydrocarbons														
Non Methane Hydrocarb														
VOC's														
5 Gas (Dry)														
THC (ppm)	40.74		70.26		35.42		28.13		51.55		97.97		14.70	
THC(%)	0.0041		0.0070		0.0035		0.0028		0.0052		0.0098		0.0015	
O2 (%)	8.85		11.19		5.43		6.96		9.11		11.29		5.13	
NOx (ppm)	24.45		32.10		2.08		4.00		15.16		25.64		3.18	
CO2 (%)	8.11		6.57		10.52		9.47		7.99		6.53		10.71	
CO2 (ppm)	81116.49		65678.51		105176.75		94676.37		79900.42		65297.93		107100.33	
CO (ppm)	4.00		3.58		3.16		3.26		4.92		9.43		2.85	
CO (%)	0.00		0.00		0.00		0.00		0.00		0.00		0.00	
N_2 Value	0.02		0.02		0.01		0.01		0.02		0.02		0.01	
NMHC (ppm)	14.99		18.42		33.02		25.35		28.33		42.67		12.71	

Figure C4. Raw FTIR and 5-Gas Data

Date Sampled	1/13/2017		1/13/2017		1/13/2017		1/13/2017		1/13/2017		1/13/2017		1/13/2017	
Fuel Composition	DF: E85		DF: E85		DF: E85		Diesel		Diesel - Repeat		DF: E85		DF: E85	
Engine Speed (rpm)	1800		2453		2465		1800		1797		1802		1801	
Engine Torque (N-m)	750.5		498		251.3		750.5		750.7		750.7		750.5	
Engine Power (kW)	141.4657977		127.9249165		64.86906876		141.4657977		141.2676576		141.6607229		141.5443898	
Test Number	23 - Post-AT		24 - Post-AT		25 - Post-AT		26 - Post-AT		27 - Pre-AT		28 - Pre-AT		29 - Pre-AT	
FTIR (Wet) [PPM]														
Component	Concentration	Std Dev	Concentration	Std Dev	Concentration	Std Dev	Concentration	Std Dev	Concentration	Std Dev	Concentration	Std Dev	Concentration	Std Dev
Carbon Monoxide high	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Carbon Dioxide	88093.07547	679.86858	72559.16851	480.64349	60987.77745	434.95496	96611.23374	683.98474	97321.62407	665.45369	96501.12996	613.98313	88372.43571	910.35559
Nitric oxide	6.48173	0.60666	18.47423	0.47595	23.31902	0.80192	3.80009	0.29984	411.13576	4.24988	241.47050	3.27014	456.39542	18.30770
Nitrogen dioxide	5.70203	1.03921	5.29202	0.81560	7.45386	0.62880	6.05092	1.08883	5.59454	1.10517	6.12762	1.44287	6.14501	1.67699
Methane	2.51771	0.15107	21.13819	0.28820	52.76783	0.46802	0.39688	0.14308	0.37174	0.14094	1.52766	0.16457	1.51126	0.19218
Methane (Dry)	2.481679765		20.79803238		51.87339121		0.391711155		0.36702561		1.507479721		1.490113546	
Ethylene	0.09823	0.08398	0.16763	0.09489	0.36641	0.10031	0.09869	0.08673	2.00424	0.11415	10.69224	0.23303	12.10188	0.28110
Ethane	0.00000	0.00000	0.00001	0.00036	0.81038	0.07843	0.00000	0.00000	0.00013	0.00211	0.00000	0.00000	0.00003	0.00072
Propylene	0.34613	0.29457	0.38488	0.31594	0.38364	0.30172	0.33117	0.29865	0.88878	0.34930	0.33603	0.29225	0.00000	0.00000
Formaldehyde	0.00004	0.00081	0.00030	0.00276	0.00205	0.01043	0.00000	0.00000	1.72618	0.07758	13.49418	0.26368	17.73610	0.23470
Formaldehyde (Dry)	3.87051E-05		0.000296203		0.002020141		0		1.704282857		13.31594386		17.48796535	
Water	122065.48694	1348.43436	112320.00446	1225.77070	98731.64944	1157.44029	120926.46919	1343.91484	120172.73026	1318.61696	125479.15126	1394.61894	122291.88448	1461.94412
Water (%)	12.20654869		11.23200045		9.873164944		12.09264692		12.01727303		12.54791513		12.22918845	
Propane	0.11143	0.06353	2.10665	0.10323	5.65826	0.18244	0.00000	0.00000	0.75520	0.08702	5.94747	0.22201	18.90279	0.27949
Hydrogen cyanide	0.00013	0.00362	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Ammonia	0.07870	0.18909	0.11160	0.25086	0.17309	0.31241	0.09836	0.23266	0.12664	0.27169	0.10086	0.24339	0.20217	0.34335
Ammonia (Dry)	0.077577893		0.109801013		0.170155077		0.097080517		0.12502985		0.099531661		0.199344308	
Carbon Monoxide low	0.00020	0.00201	0.88901	0.03920	1.20005	0.05253	0.00638	0.01209	35.16097	0.76837	278.57995	6.02443	392.17384	3.81783
Ethanol	0.00005	0.00145	0.00683	0.05273	0.31992	0.45084	0.00052	0.01044	0.00000	0.00000	4.02161	0.81312	14.86334	0.97722
Methanol	15.68631	0.62042	13.20866	0.60720	11.30491	0.61827	16.89575	0.61916	17.29634	0.60309	17.43093	0.65040	15.87068	0.73037
NOx														
Total Hydrocarbons														
Non Methane Hydrocarb														
VOC's														
5 Gas (Dry)														
THC (ppm)	13.81		39.04		82.75		8.72		26.95		92.87		172.97	
THC(%)	0.0014		0.0039		0.0083		0.0009		0.0027		0.0093		0.0173	
O2 (%)	6.52		9.19		11.31		5.27		5.18		5.04		6.34	
NOx (ppm)	5.29		18.04		24.87		2.33		432.99		272.86		503.04	
CO2 (%)	9.71		7.86		6.45		10.56		10.76		10.83		9.90	
CO2 (ppm)	97140.13		78585.38		64540.68		105597.16		107607.42		108252.17		99018.95	
CO (ppm)	3.54		4.73		4.78		3.12		48.37		288.33		398.86	
CO (%)	0.00		0.00		0.00		0.00		0.00		0.03		0.04	
N_2 Value	0.01		0.02		0.02		0.01		0.01		0.01		0.01	
NMHC (ppm)	11.33		18.24		30.88		8.33		26.58		91.36		171.48	

Figure C5. Gravimetric and Quartz Filter Data

Date Sampled	11/1/2016	11/1/2016	11/1/2016	1/10/2017		1/10/2017		1/10/2017	
Fuel Composition	100% Diesel	100% Diesel	100% Diesel	Diesel - Repeat		DF: 200 Proof		DF: 200 proof	
Engine Speed (rpm)	2456	2455	1807	1817		1811		1810	
Engine Torque (N-m)	250	498	750	751		751		750.6	
Engine Power (kW)	64.29787533	128.0292173	141.9213283	142.8970014		142.4251346		142.2706731	
Test Number	30 - Pre-AT	31 - Pre-AT	32 - Pre-AT	1 - Pre-AT		2 - Pre-AT		3 - Pre-AT	
Filter Weights									
Pre Weight (ug)	143550	146606	145705	94330		95003		95335	
Pre Weight (ug)	143550	146604	145705	94330		95004		95333	
Pre Weight (ug)	143549	146605	145705	94329		95003		95335	
Average Pre Weight (ug)	143550	146605	145705	94330		95003		95334	
Post Weight (ug)	143982	146855	145862	94543		95410		95521	
Post Weight (ug)	143962	146821	145851	94540		95411		95518	
Post Weight (ug)	143959	146821	145849	94540		95409		95516	
Post Weight (ug)	143958	146818	145849						
Average Post Weight (ug)	143960	146820	145850	94541		95410		95518	
Mass Gained Raw (ug)				211		407		184	
Mass Gained w/ Background Corrected(ug)	410	215	145	89		284		61	
Dilution Ratio	20	20	20	20.17475728		20		20	
Sample Time (s)	1200	1200	1200	1200		1200		1200	
Quartz Filter Solo Train				20170110-Q2		20170110-Q4		20170110-Q6	
OC(ug/sq cm) /// OC Uncertainty				13.81002	0.7905012	17.90874	0.995437	13.16059	0.7580297
EC(ug/sq cm) /// EC Uncertainty				6.813122	0.4406561	15.63892	0.8819457	5.452301	0.372615
Quartz Filter Duo Teflon				20170110-Q1		20170110-Q3		20170110-Q5	
OC(ug/sq cm) /// OC Uncertainty				7.225615	0.4612808	8.006623	0.5003312	8.056174	0.5028087
EC(ug/sq cm) /// EC Uncertainty				-1.50E-04	1.00E-01	1.49E-04	0.1000075	0	0.1
Filter Diameter (inches)	1.528	1.528	1.528	1.528		1.528		1.528	
Filter Area (sq cm)	11.83	11.83	11.83	11.83		11.83		11.83	
Total Carbon (ug) Q-even /// Q-odd				244	85	397	95	220	95
EC/TC Ratio Q-even /// Q-odd				0.33	0.00	0.47	0.00	0.29	0.00
EC/PM				0.38		0.45		0.35	

Figure C6. Gravimetric and Quartz Filter Data 13

Date Sampled	1/10/2017		1/10/2017		1/10/2017		1/12/2017		1/12/2017		1/12/2017	
Fuel Composition	DF: 200 proof		DF: 200 proof		DF: 200 proof		Diesel - Repeat		DF: 190 proof		DF: 190 proof	
Engine Speed (rpm)	1815		1808		1822		1816		1813		1812	
Engine Torque (N-m)	750.6		751.1		751		751.4		750.5		750.4	
Engine Power (kW)	142.663686		142.2081345		143.2902237		142.8944253		142.4874951		142.3899278	
Test Number	4 - Pre-AT		5 - Post-AT		7 - Post-AT		11 - Pre-AT		12 - Pre-AT		14 - Pre-AT	
Filter Weights												
Pre Weight (ug)	95647		93808		94074		93947		94331		94438	
Pre Weight (ug)	95646		93807		94073		93946		94331		94437	
Pre Weight (ug)	95644		93807		94073		93945		94330		94436	
Average Pre Weight (ug)	95646		93807		94073		93946		94331		94437	
Post Weight (ug)	95787		94055		94421		94183		94712		94655	
Post Weight (ug)	95785		94053		94418		94182		94711		94651	
Post Weight (ug)	95783		94055		94419		94181		94709		94653	
Post Weight (ug)												
Average Post Weight (ug)	95785		94054		94419		94182		94711		94653	
Mass Gained Raw (ug)	139		247		346		236		380		216	
Mass Gained w/ Background Corrected(ug)	17		124		223		113		257		93	
Dilution Ratio	20		20		20		20		20		20	
Sample Time (s)	1200		1200		1200		1200		1200		1200	
Quartz Filter Solo Train	20170110-Q8		20170110-Q10		20170110-Q12		20170112-Q2		20170112-Q4		20170112-Q6	
OC(ug/sq cm) /// OC Uncertainty	5.54932	0.377466	13.27164	0.7635819	22.16782	1.208391	9.902074	0.5951037	14.07008	0.8035041	11.56754	0.6783769
EC(ug/sq cm) /// EC Uncertainty	1.076306	0.1538153	12.38146	0.7190731	8.309806	0.5154903	9.784148	0.5892074	16.94479	0.9472396	6.57621	0.4288105
Quartz Filter Duo Teflon	20170110-Q7		20170110-Q9		20170110-Q11		20170112-Q1		20170112-Q3		20170112-Q5	
OC(ug/sq cm) /// OC Uncertainty	7.224958	0.4612479	6.74621	0.4373105	7.359717	0.4679858	4.625961	0.3312981	6.059251	0.4029626	5.112813	0.3556407
EC(ug/sq cm) /// EC Uncertainty	1.49E-04	0.1000075	0	0.1	4.45E-04	0.1000223	-1.49E-04	1.00E-01	0	0.1	0	0.1
Filter Diameter (inches)	1.528		1.528		1.528		1.528		1.528		1.528	
Filter Area (sq cm)	11.83		11.83		11.83		11.83		11.83		11.83	
Total Carbon (ug) Q-even /// Q-odd	78	85	303	80	361	87	233	55	367	72	215	60
EC/TC Ratio Q-even /// Q-odd	0.16	0.00	0.48	0.00	0.27	0.00	0.50	0.00	0.55	0.00	0.36	0.00
EC/PM	0.09		0.59		0.28		0.49		0.53		0.36	

Figure C7. Gravimetric and Quartz Filter Data

Date Sampled	1/12/2017		1/12/2017		1/13/2017		1/13/2017		1/13/2017		1/13/2017		1/13/2017	
Fuel Composition	DF: 200 proof		DF: 200 proof		DF: 190 proof		DF: 190 proof		DF: 190 proof		DF: 190 proof		DF: E85	
Engine Speed (rpm)	2447		2449		1813		1813		2436		2473		1805	
Engine Torque (N-m)	496.8		251.1		751.1		751.1		497.9		251.3		750.6	
Engine Power (kW)	127.3045153		64.39672023		142.6014092		142.6014092		127.0128501		65.07959717		141.8776601	
Test Number	15 - Post-AT		16 - Post-AT		17 - Post-AT		19 - Post-AT		20 - Post-AT		21 - Post-AT		22 - Post-AT	
Filter Weights														
Pre Weight (ug)	96290		95787		94720		91810		93770		93915		92286	
Pre Weight (ug)	96289		95787		94719		91811		93767		93915		92290	
Pre Weight (ug)	96289		95788		94718		91810		93767		93914		92290	
Average Pre Weight (ug)	96289		95787		94719		91810		93768		93915		92289	
Post Weight (ug)	96704		96111		95008		91950		94178		94258		92629	
Post Weight (ug)	96712		96110		95007		91949		94178		94257		92628	
Post Weight (ug)	96706		96111		95005		91948		94176		94258		92629	
Post Weight (ug)	96709													
Average Post Weight (ug)	96708		96111		95007		91949		94177		94258		92629	
Mass Gained Raw (ug)	418		323		288		139		409		343		340	
Mass Gained w/ Background Corrected(ug)	296		201		165		16		287		220		217	
Dilution Ratio	20		20		20		20		20		20		20	
Sample Time (s)	1200		1200		1200		1200		1200		1200		1200	
Quartz Filter Solo Train	20170112-Q8		20170112-Q10		20170113-Q2		20170113-Q4		20170113-Q6		20170113-Q8		20170113-Q10	
OC(ug/sq cm) /// OC Uncertainty	12.60325	0.7301623	11.38096	0.6690481	10.42538	0.6212689	8.014534	0.5007267	12.15411	0.7077057	10.53061	0.6265303	12.37773	0.7188863
EC(ug/sq cm) /// EC Uncertainty	20.7674	1.13837	14.02589	0.8012945	13.64365	0.7821823	5.799919	0.389996	20.00751	1.100375	13.13052	0.7565262	15.00497	0.8502485
Quartz Filter Duo Teflon	20170112-Q7		20170112-Q9		20170113-Q1		20170113-Q3		20170113-Q5		20170113-Q7		20170113-Q9	
OC(ug/sq cm) /// OC Uncertainty	5.87464	0.393732	5.58399	0.3791995	4.401809	0.3200904	5.172905	0.3586453	5.18381	0.3591905	5.298288	0.3649144	5.518314	0.3759157
EC(ug/sq cm) /// EC Uncertainty	0	0.1	0	0.1	0	0.1	1.48E-04	0.1000074	-1.50E-04	0.0999925	1.49E-04	0.1000074	-1.50E-04	1.00E-01
Filter Diameter (inches)	1.528		1.528		1.528		1.528		1.528		1.528		1.528	
Filter Area (sq cm)	11.83		11.83		11.83		11.83		11.83		11.83		11.83	
Total Carbon (ug) Q-even /// Q-odd	395	70	301	66	285	52	163	61	380	61	280	63	324	65
EC/TC Ratio Q-even /// Q-odd	0.62	0.00	0.55	0.00	0.57	0.00	0.42	0.00	0.62	0.00	0.55	0.00	0.55	0.00
EC/PM	0.59		0.51		0.56		0.49		0.58		0.45		0.52	

Date Sampled	1/13/2017		1/13/2017		1/13/2017		1/13/2017		1/13/2017		1/13/2017		1/13/2017	
Fuel Composition	DF: E85		DF: E85		DF: E85		Diesel		Diesel - Repeat		DF: E85		DF: E85	
Engine Speed (rpm)	1800		2453		2465		1800		1797		1802		1801	
Engine Torque (N-m)	750.5		498		251.3		750.5		750.7		750.7		750.5	
Engine Power (kW)	141.4657977		127.9249165		64.86906876		141.4657977		141.2676576		141.6607229		141.5443898	
Test Number	23 - Post-AT		24 - Post-AT		25 - Post-AT		26 - Post-AT		27 - Pre-AT		28 - Pre-AT		29 - Pre-AT	
Filter Weights														
Pre Weight (ug)	93045		97962		92994		93531		92626		91514		94875	
Pre Weight (ug)	93043		97960		92994		93530		92626		91514		94876	
Pre Weight (ug)	93045		97960		92993		93531		92626		91511		94865	
Average Pre Weight (ug)	93044		97961		92994		93531		92626		91513		94872	
Post Weight (ug)	93210		98380		93332		93716		92878		91918		95162	
Post Weight (ug)	93209		98380		93331		93712		92879		91917		95159	
Post Weight (ug)	93208		98376		93332		93714		92882		91919		95159	
Post Weight (ug)														
Average Post Weight (ug)	93209		98379		93332		93714		92880		91918		95160	
Mass Gained Raw (ug)	165		418		338		183		254		405		288	
Mass Gained w/ Background Corrected(ug)	42		295		215		61		131		282		165	
Dilution Ratio	21		21		20		20		20		20		20	
Sample Time (s)	1200		1200		1200		1200		1200		1200		1200	
Quartz Filter Solo Train	20170113-Q12		20170113-Q14		20170113-Q16		20170113-Q18		20170113-Q20		20170113-Q22		20170113-Q24	
OC(ug/sq cm) /// OC Uncertainty	8.376157	0.5188078	10.30993	0.6154963	9.369502	0.5684751	9.092365	0.5546182	10.54093	0.6270462	15.09509	0.8547544	12.18195	0.7090975
EC(ug/sq cm) /// EC Uncertainty	6.006208	0.4003104	20.14411	1.107205	13.94662	0.7973312	7.63471	0.4817355	9.274059	0.5637029	17.82238	0.9911191	8.834783	0.5417391
Quartz Filter Duo Teflon	20170113-Q11		20170113-Q13		20170113-Q15		20170113-Q17		20170113-Q19		20170113-Q21		20170113-Q23	
OC(ug/sq cm) /// OC Uncertainty	5.43892	0.371946	4.380629	0.3190314	4.650759	0.3325379	6.278504	0.4139252	5.567291	0.3783645	6.197046	0.4098523	7.001556	0.4500778
EC(ug/sq cm) /// EC Uncertainty	0	0.1	-1.51E-04	1.00E-01	-1.50E-04	1.00E-01	-1.49E-04	1.00E-01	-2.99E-04	1.00E-01	0	0.1	1.48E-04	0.1000074
Filter Diameter (inches)	1.528		1.528		1.528		1.528		1.528		1.528		1.528	
Filter Area (sq cm)	11.83		11.83		11.83		11.83		11.83		11.83		11.83	
Total Carbon (ug) Q-even /// Q-odd	170	64	360	52	276	55	198	74	234	66	389	73	249	83
EC/TC Ratio Q-even /// Q-odd	0.42	0.00	0.66	0.00	0.60	0.00	0.46	0.00	0.47	0.00	0.54	0.00	0.42	0.00
EC/PM	0.43		0.57		0.49		0.49		0.43		0.52		0.36	

Figure C8. Gravimetric and Quartz Filter Data

Date Sampled	11/1/2016	11/1/2016	11/1/2016	1/10/2017	1/10/2017	1/10/2017
Fuel Composition	100% Diesel	100% Diesel	100% Diesel	Diesel - Repeat	DF: 200 Proof	DF: 200 proof
Engine Speed (rpm)	2456	2455	1807	1817	1811	1810
Engine Torque (N-m)	250	498	750	751	751	750.6
Engine Power (kW)	64.29787533	128.0292173	141.9213283	142.8970014	142.4251346	142.2706731
Test Number	30 - Pre-AT	31 - Pre-AT	32 - Pre-AT	1 - Pre-AT	2 - Pre-AT	3 - Pre-AT
Calterm						
Diesel Consumption (kg/min)	0.272	0.512	0.512	0.515	0.454	0.385
Diesel Consumption Corrected (kg/hr)	17.2	31.8	31.8	32.0	28.3	24.1
Dual Fuel Consumption (kg/hr)	0.0	0.0	0.0	0.0	6.0	10.0
Total Consumption (kg/hr)	17.2	31.8	31.8	32.0	34.3	34.1
Diesel Substitution (%)					12%	25%
Cost of Operation ($/hr)	14.05	25.96	25.97	26.12		
BSE Emissions						
Molecular Fuel Consumption Diesel (kmol/hr)	0.087030833	0.160778115	0.160850959	0.161770486	0.142898354	0.121716015
Mass Fraction Fuel Consumption Diesel	1	1	1	1	0.825481876	0.706832641
Molecular FC Dual Fuel (kmol/hr)	0	0	0	0	0.129749501	0.216816445
Mass Fraction FC Dual Fuel	0	0	0	0	0.174518124	0.293167359
Total Molecular FC (kmol/hr)	0.087030833	0.160778115	0.160850959	0.161770486	0.272647855	0.33853246
Mol Fraction FC Diesel	1	1	1	1	0.524113253	0.35954016
Mol Fraction FC DF	0	0	0	0	0.475886747	0.64045984
Total Carbon (alpha)	14.4	14.4	14.4	14.4	8.499004336	6.458297982
Total Hydrogen (beta)	24.9	24.9	24.9	24.9	15.90574048	12.79530902
Total Oxygen (gamma)	0	0	0	0	0.475886747	0.64045984
Percent Conversion THC (% dry)	0.007110516	0.005517488	0.006267737	0.003116098	0.010204579	0.017677648
Percent Conversion CO (% dry)	0.006266822	0.003814043	0.004665624	0.005219865	0.029695047	0.041339032
Percent Conversion NOx (% dry)	0.031165659	0.041279458	0.047162925	0.034207973	0.021025095	0.04520255
Y Value	1.729166667	1.729166667	1.729166667	1.729166667	1.871482806	1.981219983
Z Value	0	0	0	0	0.055993235	0.099168518
H2FAC	0.001549159	0.000942479	0.00115285	0.001289887	0.007954885	0.011736616
A' Value Calculation	3.401608133	2.686833084	1.873406441	1.937815596	1.905571175	2.143151731
Equivalence Ratio	0.4210631	0.533078022	0.764538669	0.739126917	0.755612859	0.67457694
AF Stoic	14.37488034	14.37488034	14.37488034	14.37488034	13.4357448	12.7970679
AF Actual	34.13949198	26.96580938	18.80203176	19.44846009	17.78125482	18.97050899
M_dot PM FS (kg/s)	3.41667E-10	1.79167E-10	1.20556E-10	7.38889E-11	2.36667E-10	5.11111E-11
M_dot FS (SLPM)	14.15	14.15	14.15	14.15	14.15	14.15
M_dot FS (kg/s)	0.000288902	0.000288902	0.000288902	0.000288902	0.000288902	0.000288902
f_pm FS	1.18264E-06	6.20165E-07	4.17289E-07	2.55758E-07	8.19194E-07	1.76915E-07
M_dot exhaust (kg/s)	0.168078032	0.247113607	0.175055493	0.181803497	0.178684394	0.189000344
BSE Nox (g/bkW-hr)	4.377	4.231	3.015	2.422	1.458	3.312
BSE CO (g/bkW-hr)	0.536	0.238	0.182	0.225	1.254	1.844
BSE THC (g/bkW-hr)	0.348	0.197	0.140	0.077	0.247	0.452
BSE PM (g/bkW-hr)	0.236	0.092	0.039	0.025	0.079	0.018
BSE NMHC (g/bkW-hr)	0.343	0.195	0.139	0.076	0.243	0.448
BSE Formaldehyde (mg/bkW-hr)	9.636	4.596	7.605	8.937	60.587	83.474
BSE Ammonia (mg/bkW-hr)	0.524	0.350	0.000	0.590	0.501	0.766
Total Oxidation Emissions (g/bkW-hr)	1.116	0.525	0.360	0.326	1.576	2.310
Total Oxidatino Efficiency						
Efficiency	31.41%	33.85%	37.51%	37.55%	37.40%	39.42%

Figure C9. BSE Calculations

Figure C10. BSE Calculations

Date Sampled	1/10/2017	1/10/2017	1/10/2017	1/12/2017	1/12/2017	1/12/2017
Fuel Composition	DF: 200 proof	DF: 200 proof	DF: 200 proof	Diesel - Repeat	DF: 190 proof	DF: 190 proof
Engine Speed (rpm)	1815	1808	1822	1816	1813	1812
Engine Torque (N-m)	750.6	751.1	751	751.4	750.5	750.4
Engine Power (kW)	142.663686	142.2081345	143.2902237	142.8944253	142.4874951	142.3899278
Test Number	4 - Pre-AT	5 - Post-AT	7 - Post-AT	11 - Pre-AT	12 - Pre-AT	14 - Pre-AT
Calterm						
Diesel Consumption (kg/min)	0.382	0.460	0.389	0.523	0.462	0.387
Diesel Consumption Corrected (kg/hr)	23.9	28.7	24.4	32.5	28.8	24.2
Dual Fuel Consumption (kg/hr)	10.6	5.8	10.0	0.0	5.7	9.3
Total Consumption (kg/hr)	34.5	34.5	34.4	32.5	34.5	33.5
Diesel Substitution (%)	26%	11%	25%		11%	25%
Cost of Operation ($/hr)						
BSE Emissions						
Molecular Fuel Consumption Diesel (kmol/hr)	0.120984867	0.144807142	0.123136705	0.164111039	0.145324873	0.122481505
Mass Fraction Fuel Consumption Diesel	0.692929308	0.830548824	0.709231559	1	0.834557739	0.722923727
Molecular FC Dual Fuel (kmol/hr)	0.230263958	0.126886342	0.216816445	0	0.123730138	0.201615004
Mass Fraction FC Dual Fuel	0.307070692	0.169451176	0.290768441	0	0.165442261	0.277076273
Total Molecular FC (kmol/hr)	0.351248825	0.271693483	0.33995315	0.164111039	0.269055011	0.324096509
Mol Fraction FC Diesel	0.344442055	0.532979811	0.36221669	1	0.540130706	0.377916768
Mol Fraction FC DF	0.655557945	0.467020189	0.63778331	0	0.459869294	0.622083232
Total Carbon (alpha)	6.271081483	8.60894966	6.491486962	14.4	8.697620756	6.686167917
Total Hydrogen (beta)	12.50995484	16.07331843	12.84589545	24.9	16.20847035	13.14262691
Total Oxygen (gamma)	0.655557945	0.467020189	0.63778331	0	0.459869294	0.622083232
Percent Conversion THC (% dry)	0.018164013	0.001186153	0.000994408	0.002806486	0.009987079	0.018558289
Percent Conversion CO (% dry)	0.042269226	0.000340241	0.000344942	0.005351715	0.027362854	0.039216402
Percent Conversion NOx (% dry)	0.042681829	0.00078658	0.000812769	0.041578632	0.026292987	0.05575621
Y Value	1.994864024	1.867047557	1.978883348	1.729166667	1.863552206	1.965644158
Z Value	0.104536665	0.054248219	0.098249186	0	0.052872999	0.093040324
H2FAC	0.012083937	9.07516E-05	9.75167E-05	0.001322472	0.007297837	0.011044232
A' Value Calculation	2.124553744	1.882184249	2.091396142	1.929965067	1.920616136	2.142718906
Equivalence Ratio	0.680824233	0.764876117	0.691211108	0.742133467	0.749473841	0.674325911
AF Stoic	12.72221765	13.46301626	12.80998256	14.37488034	13.48459295	12.88369357
AF Actual	18.68649356	17.60156444	18.53266305	19.36966998	17.99207953	19.1060337
M_dot PM FS (kg/s)	1.38889E-11	1.03611E-10	1.86111E-10	9.44444E-11	2.14444E-10	7.77778E-11
M_dot FS (SLPM)	14.15	14.15	14.15	14.15	14.15	14.15
M_dot FS (kg/s)	0.000288902	0.000288902	0.000288902	0.000288902	0.000288902	0.000288902
f_pm FS	4.80748E-08	3.58638E-07	6.44202E-07	3.26909E-07	7.42274E-07	2.69219E-07
M_dot exhaust (kg/s)	0.188909076	0.178244697	0.1863817	0.183723251	0.181760044	0.187217644
BSE Nox (g/bkW-hr)	3.121	0.055	0.059	2.935	1.829	3.986
BSE CO (g/bkW-hr)	1.882	0.015	0.015	0.230	1.159	1.707
BSE THC (g/bkW-hr)	0.463	0.029	0.025	0.069	0.242	0.463
BSE PM (g/bkW-hr)	0.005	0.034	0.064	0.032	0.073	0.027
BSE NMHC (g/bkW-hr)	0.459	0.025	0.019	0.068	0.238	0.459
BSE Formaldehyde (mg/bkW-hr)	85.427	0.000	0.001	9.129	59.170	83.275
BSE Ammonia (mg/bkW-hr)	0.670	1.009	0.906	0.905	0.400	0.911
Total Oxidation Emissions (g/bkW-hr)	2.346	0.073	0.098	0.330	1.471	2.193
Total Oxidatino Efficiency		95%	96%			
Efficiency	39.21%	37.00%	39.33%	37.02%	37.02%	39.74%

Date Sampled	1/12/2017	1/12/2017	1/13/2017	1/13/2017	1/13/2017	1/13/2017	1/13/2017
Fuel Composition	DF: 200 proof	DF: 200 proof	DF: 190 proof	DF: 190 proof	DF: 190 proof	DF: 190 proof	DF: E85
Engine Speed (rpm)	2447	2449	1813	1813	2436	2473	1805
Engine Torque (N-m)	496.8	251.1	751.1	751.1	497.9	251.3	750.6
Engine Power (kW)	127.3045153	64.39672023	142.6014092	142.6014092	127.0128501	65.07959717	141.8776601
Test Number	15 - Post-AT	16 - Post-AT	17 - Post-AT	19 - Post-AT	20 - Post-AT	21 - Post-AT	22 - Post-AT
Calterm							
Diesel Consumption (kg/min)	0.287	0.199	0.432	0.384	0.316	0.203	0.457
Diesel Consumption Corrected (kg/hr)	18.1	12.8	27.0	24.1	19.9	13.0	28.5
Dual Fuel Consumption (kg/hr)	17.6	8.3	5.9	9.7	15.3	9.1	5.7
Total Consumption (kg/hr)	35.8	21.1	32.9	33.8	35.2	22.1	34.1
Diesel Substitution (%)	43%	26%	16%	25%	37%	24%	12%
Cost of Operation ($/hr)							26.83
BSE Emissions							
Molecular Fuel Consumption Diesel (kmol/hr)	0.091645927	0.064772643	0.136392469	0.12158083	0.100617243	0.065791896	0.143816384
Mass Fraction Fuel Consumption Diesel	0.507054054	0.607499722	0.819893151	0.712468468	0.565433797	0.588981405	0.833404832
Molecular FC Dual Fuel (kmol/hr)	0.382651732	0.179734306	0.128679344	0.210731961	0.332117739	0.197186767	0.114275953
Mass Fraction FC Dual Fuel	0.492945946	0.392500278	0.180106849	0.287531532	0.434566203	0.411018595	0.166595168
Total Molecular FC (kmol/hr)	0.474297659	0.244506949	0.265071812	0.332312791	0.432734982	0.262978664	0.258092337
Mol Fraction FC Diesel	0.193224497	0.264911256	0.514549124	0.365862624	0.232514696	0.250179598	0.557228416
Mol Fraction FC DF	0.806775503	0.735088744	0.485450876	0.634137376	0.767485304	0.749820402	0.442771584
Total Carbon (alpha)	4.395983768	5.284899574	8.380409136	6.536696534	4.883182232	5.102227014	9.054034188
Total Hydrogen (beta)	9.651943001	11.00682274	15.72497844	12.91480359	10.39452776	10.7283944	16.82042072
Total Oxygen (gamma)	0.806775503	0.735088744	0.485450876	0.634137376	0.767485304	0.749820402	0.418704612
Percent Conversion THC (% dry)	0.004073514	0.007025821	0.003542408	0.0028132	0.005155058	0.009796683	0.001470475
Percent Conversion CO (% dry)	0.000400209	0.000357831	0.000315567	0.000325833	0.000492325	0.000943242	0.000285258
Percent Conversion NOx (% dry)	0.002444831	0.003209829	0.000208364	0.000400011	0.00151561	0.002564469	0.000318296
Y Value	2.195627534	2.082692884	1.876397463	1.975738589	2.128638102	2.102688565	1.857781887
Z Value	0.183525587	0.139092282	0.057926871	0.097011904	0.157169089	0.146959436	0.046245088
H2FAC	0.000125534	0.000106469	8.45916E-05	9.19682E-05	0.000149718	0.000283364	7.57083E-05
A' Value Calculation	2.547487416	3.151651987	1.956040164	2.180368653	2.591814118	3.176973985	1.920435942
Equivalence Ratio	0.571992655	0.460433793	0.736250695	0.66292858	0.560833036	0.457099249	0.750518617
AF Stoic	11.72133412	12.26225113	13.40566468	12.82740846	12.03573232	12.16253509	13.60540183
AF Actual	20.49210602	26.63195296	18.20801633	19.34960845	21.46045534	26.60808371	18.12800045
M_dot PM FS (kg/s)	2.46458E-10	1.67222E-10	1.375E-10	1.33333E-11	2.38889E-10	1.83611E-10	1.81111E-10
M_dot FS (SLPM)	14.15	14.15	14.15	14.15	14.15	14.15	14.15
M_dot FS (kg/s)	0.000288902	0.000288902	0.000288902	0.000288902	0.000288902	0.000288902	0.000288902
f_pm FS	8.53087E-07	5.7882E-07	4.7594E-07	4.61518E-08	8.26886E-07	6.35549E-07	6.26895E-07
M_dot exhaust (kg/s)	0.213491317	0.16191961	0.175613534	0.190852497	0.219660283	0.169492083	0.181411268
BSE Nox (g/bkW-hr)	0.226	0.448	0.014	0.030	0.145	0.369	0.022
BSE CO (g/bkW-hr)	0.023	0.030	0.013	0.015	0.029	0.083	0.012
BSE THC (g/bkW-hr)	0.132	0.342	0.084	0.072	0.172	0.492	0.036
BSE PM (g/bkW-hr)	0.109	0.110	0.044	0.005	0.109	0.128	0.061
BSE NMHC (g/bkW-hr)	0.048	0.090	0.078	0.065	0.094	0.215	0.031
BSE Formaldehyde (mg/bkW-hr)	0.002	0.002	0.000	0.000	0.001	1.123	0.001
BSE Ammonia (mg/bkW-hr)	0.546	0.947	0.216	0.293	0.375	0.773	0.194
Total Oxidation Emissions (g/bkW-hr)	0.180	0.231	0.135	0.085	0.232	0.426	0.105
Total Oxidatino Efficiency			91%	96%			93%
Efficiency	36.66%	30.06%	39.00%	39.68%	36.05%	29.13%	36.92%

Figure C11. BSE Calculations

Figure C12. BSE Calculations

Date Sampled	1/13/2017	1/13/2017	1/13/2017	1/13/2017	1/13/2017	1/13/2017	1/13/2017
Fuel Composition	DF: E85	DF: E85	DF: E85	Diesel	Diesel - Repeat	DF: E85	DF: E85
Engine Speed (rpm)	1800	2453	2465	1800	1797	1802	1801
Engine Torque (N-m)	750.5	498	251.3	750.5	750.7	750.7	750.5
Engine Power (kW)	141.4657977	127.9249165	64.86906876	141.4657977	141.2676576	141.6607229	141.5443898
Test Number	23 - Post-AT	24 - Post-AT	25 - Post-AT	26 - Post-AT	27 - Pre-AT	28 - Pre-AT	29 - Pre-AT
Calterm							
Diesel Consumption (kg/min)	0.394	0.309	0.201	0.526	0.521	0.453	0.390
Diesel Consumption Corrected (kg/hr)	24.6	19.5	12.9	32.7	32.4	28.2	24.4
Dual Fuel Consumption (kg/hr)	8.0	14.8	8.4	0.0	0.0	5.8	8.8
Total Consumption (kg/hr)	32.7	34.3	21.3	32.7	32.4	34.0	33.2
Diesel Substitution (%)	24%	39%	25%			13%	24%
Cost of Operation ($/hr)	25.19	25.31	15.85	26.69	26.42	26.71	25.47
BSE Emissions							
Molecular Fuel Consumption Diesel (kmol/hr)	0.124579348	0.098558368	0.065171061	0.165288612	0.163630861	0.142736229	0.123198388
Mass Fraction Fuel Consumption Diesel	0.754873454	0.568183924	0.605245031	1	1	0.830007017	0.734830965
Molecular FC Dual Fuel (kmol/hr)	0.160806035	0.297744308	0.168962863	0	0	0.116204661	0.176717876
Mass Fraction FC Dual Fuel	0.245126546	0.431816076	0.394754969	0	0	0.169992983	0.265169035
Total Molecular FC (kmol/hr)	0.285385383	0.396302676	0.234133923	0.165288612	0.163630861	0.25894089	0.299916265
Mol Fraction FC Diesel	0.436530234	0.248694683	0.2783495	1	1	0.551230936	0.410775949
Mol Fraction FC DF	0.563469766	0.751305317	0.7216505	0	0	0.448769064	0.589224051
Total Carbon (alpha)	7.596740226	5.328838517	5.686886881	14.4	14.4	8.981621403	7.28578638
Total Hydrogen (beta)	14.61795207	11.19037841	11.73151171	24.9	24.9	16.71098028	14.14799466
Total Oxygen (gamma)	0.532842211	0.710467909	0.682424987	0	0	0.424376098	0.557196615
Percent Conversion THC (% dry)	0.001380733	0.003903842	0.008275492	0.000872227	0.002694933	0.009286833	0.017296967
Percent Conversion CO (% dry)	0.000354167	0.000473192	0.000478375	0.00031241	0.004837342	0.028832783	0.039886233
Percent Conversion NOx (% dry)	0.000529112	0.001803728	0.002486508	0.000233347	0.043299188	0.027285655	0.050303906
Y Value	1.924240087	2.099965756	2.062905761	1.729166667	1.729166667	1.860575005	1.941862405
Z Value	0.070140902	0.133325096	0.119999747	0	0	0.047249386	0.07647721
H2FAC	9.73599E-05	0.000141961	0.000140985	7.71744E-05	0.001195322	0.00767822	0.011096596
A' Value Calculation	2.116806739	2.62677174	3.204663996	1.930951582	1.917086982	1.905078736	2.084229293
Equivalence Ratio	0.683099474	0.555179146	0.45425248	0.741754314	0.747118769	0.756671643	0.694370337
AF Stoic	13.24258491	12.3798377	12.55113452	14.37488034	14.37488034	13.58970506	13.14997865
AF Actual	19.38602707	22.29881615	27.6303049	19.37957092	19.24042191	17.95984451	18.93799023
M_dot PM FS (kg/s)	3.5E-11	2.46111E-10	1.79444E-10	5.05556E-11	1.09167E-10	2.35278E-10	1.37778E-10
M_dot FS (SLPM)	14.15	14.15	14.15	14.15	14.15	14.15	14.15
M_dot FS (kg/s)	0.000288902	0.000288902	0.000288902	0.000288902	0.000288902	0.000288902	0.000288902
f_pm FS	1.21148E-07	8.51885E-07	6.21126E-07	1.74992E-07	3.77868E-07	8.14387E-07	4.76902E-07
M_dot exhaust (kg/s)	0.184904223	0.222116464	0.169430606	0.185131493	0.182023354	0.179196516	0.183713593
BSE Nox (g/bkW-hr)	0.038	0.174	0.361	0.017	3.072	1.883	3.546
BSE CO (g/bkW-hr)	0.016	0.028	0.042	0.014	0.209	1.211	1.712
BSE THC (g/bkW-hr)	0.035	0.131	0.419	0.022	0.067	0.223	0.425
BSE PM (g/bkW-hr)	0.012	0.115	0.125	0.018	0.036	0.079	0.047
BSE NMHC (g/bkW-hr)	0.029	0.061	0.157	0.021	0.066	0.220	0.421
BSE Formaldehyde (mg/bkW-hr)	0.000	0.002	0.019	0.000	7.893	59.973	80.469
BSE Ammonia (mg/bkW-hr)	0.208	0.392	0.914	0.263	0.328	0.254	0.520
Total Oxidation Emissions (g/bkW-hr)	0.057	0.204	0.325	0.053	0.311	1.510	2.181
Total Oxidatino Efficiency	97%			83%			
Efficiency	39.55%	36.39%	29.32%	36.39%	36.70%	37.04%	39.22%

Date Sampled	11/1/2016	11/1/2016	11/1/2016	1/10/2017	1/10/2017	1/10/2017
Fuel Composition	100% Diesel	100% Diesel	100% Diesel	Diesel - Repeat	DF: 200 Proof	DF: 200 proof
Engine Speed (rpm)	2456	2455	1807	1817	1811	1810
Engine Torque (N-m)	250	498	750	751	751	750.6
Engine Power (kW)	64.29787533	128.0292173	141.9213283	142.8970014	142.4251346	142.2706731
Test Number	30 - Pre-AT	31 - Pre-AT	32 - Pre-AT	1 - Pre-AT	2 - Pre-AT	3 - Pre-AT
Calterm Parameters Cont.						
CBR_Main_SOI (deg BTDC)	1.0	2.7	1.9	1.8	-0.2	-0.6
CBP_Air_Fuel Ratio	39.2	28.6	20.9	21.1	22.7	26.7
EGR_Flow (kg/min)	2.7	3.2	2.3	2.4	2.6	1.8
EGR_Position (%)	22.4	19.5	13.4	13.0	18.1	101.6
Exhuast Flow (kg/min)	10.9	15.2	11.2	11.4	10.8	10.6
Filtrered Turbo Speed (kRPM)	100.6	125.8	115.2	115.2	113.0	107.1
Charge Flow (kg/min)	13.4	17.9	13.0	13.2	12.9	12.1
Exhaust Pressure (kPa)	274.1	369.8	360.9	358.3	327.3	229.0
DOC Inlet Temp (Deg C)				459.9	461.0	435.8
DOC Outlet Temp (Deg C)				457.4	462.5	442.2
DOC Delta Temp (Deg C)				-2.5	1.5	6.5
SCR Inlet Temp (Deg C)				437.7	443.8	422.4
SCR Outlet Temp (Deg C)				440.1	444.6	427.6
AFT Intake NOx (ppm)				376.2	244.9	528.1
AFT Outlet NOx (ppm)				4.9	7.9	7.9
Charge Temp (Deg C)	56.2	79.9	72.1	68.3	66.6	55.7
Exhaust Temp (Deg C)	405.1	548.1	626.7	616.5	570.8	508.3
Charge Pressure (kPa)	177.4	251.1	238.2	238.3	231.0	204.8
EGR Delta Pressure (kPa)	4.8	4.8	3.0	3.2	3.7	3.1
Compressor Outlet Temp (Deg C)	129.5	191.6	176.8	175.6	171.4	151.9
AFT DEF Dosing Rate (g/hr)				905.1	569.0	1182.1
Nox Reduction Efficiency				0.410275842	0.416506079	0.44004791
Ambiet Temperature (Historic Data from CSU Website) (Deg C)	15.55	15.55	15.55	10	10	10
Nox Variance				10.97765	3.64741	2.95966
Nox % Deviation				2.835%	1.468%	0.564%
Calterm BSE Nox Intlet				2.663669937	1.698385668	3.869351255
Calterm BSE Nox Outlet				0.034427313	0.054825913	0.058195485
Other Data						
Maximum Cylinder Temp (K)	1397.378729	1547.37334		1782.268561	1737.500589	1871.319345
Location of Maximum Cylinder Temp (ATDC)	23.5	28.5		27	27	26.5
NO2/NO Fraction	0.050487841	0.026842133	0.023199464	0.01531588	0.023496839	0.012393578
BSEC (kJ/kW-hr)	11462	10634	9598	9587	9625	9133
BSFC (g/kW-hr)	267.807	248.464	224.244	223.986	240.479	239.475
BMEP (kPa)	468.8940299	934.0369075	1406.68209	1408.557666	1408.557666	1407.807435

Figure C13. Calterm Parameters

Date Sampled	1/10/2017	1/10/2017	1/10/2017	1/12/2017	1/12/2017	1/12/2017
Fuel Composition	DF: 200 proof	DF: 200 proof	DF: 200 proof	Diesel - Repeat	DF: 190 proof	DF: 190 proof
Engine Speed (rpm)	1815	1808	1822	1816	1813	1812
Engine Torque (N-m)	750.6	751.1	751	751.4	750.5	750.4
Engine Power (kW)	142.663686	142.2081345	143.2902237	142.8944253	142.4874951	142.3899278
Test Number	4 - Pre-AT	5 - Post-AT	7 - Post-AT	11 - Pre-AT	12 - Pre-AT	14 - Pre-AT
Calterm Parameters Cont.						
CBR_Main_SOI (deg BTDC)	-0.6	-0.1	-0.6	2.0	0.2	-0.1
CBP_Air_Fuel Ratio	26.7	22.5	26.1	20.7	22.7	26.8
EGR_Flow (kg/min)	1.8	2.5	2.0	2.3	2.6	1.8
EGR_Position (%)	101.6	15.4	101.6	12.9	16.4	101.6
Exhuast Flow (kg/min)	10.6	10.8	10.5	11.4	10.9	10.8
Filtrered Turbo Speed (kRPM)	107.2	114.2	107.6	114.6	113.1	106.0
Charge Flow (kg/min)	12.0	12.8	12.1	13.2	13.1	12.2
Exhaust Pressure (kPa)	229.4	341.0	232.0	363.9	340.6	229.3
DOC Inlet Temp (Deg C)	438.5	469.3	441.7	459.5	453.9	429.1
DOC Outlet Temp (Deg C)	445.4	470.2	448.1	457.7	455.5	436.7
DOC Delta Temp (Deg C)	6.8	0.9	6.4	-1.9	1.6	7.6
SCR Inlet Temp (Deg C)	425.4	451.2	428.5	438.3	436.9	417.2
SCR Outlet Temp (Deg C)	430.3	451.9	432.9	441.3	437.5	422.1
AFT Intake NOx (ppm)	502.9	243.7	468.3	385.0	238.5	510.0
AFT Outlet NOx (ppm)	8.1	9.9	10.7	1.5	2.9	3.8
Charge Temp (Deg C)	57.2	68.9	58.5	69.4	63.5	50.4
Exhaust Temp (Deg C)	509.5	581.8	517.4	626.9	568.1	499.1
Charge Pressure (kPa)	204.8	232.3	206.2	238.9	233.2	204.7
EGR Delta Pressure (kPa)	3.2	3.5	3.5	3.1	3.8	3.3
Compressor Outlet Temp (Deg C)	152.7	175.5	154.2	174.4	171.4	148.8
AFT DEF Dosing Rate (g/hr)	1124.3	570.1	1043.6	922.2	554.4	1140.7
Nox Reduction Efficiency	0.4400274	0.410204014	0.438476718	0.415895672	0.425035177	0.443772435
Ambiet Temperature (Historic Data from CSU Website) (Deg C)	10	10	10	0	0	0
Nox Variance	2.23308	8.95399	8.59493	12.05230	1.41845	5.20129
Nox % Deviation	0.446%	47.587%	44.570%	3.035%	0.591%	1.010%
Calterm BSE Nox Intlet	3.676773956	1.71755003	3.418101205	2.717672109	1.659101485	3.64574554
Calterm BSE Nox Outlet	0.059458584	0.069494633	0.078025852	0.010411144	0.019896826	0.026922545
Other Data						
Maximum Cylinder Temp (K)	1877.948308	1768.793267	1863.676908	1776.633538	1736.955365	1834.748686
Location of Maximum Cylinder Temp (ATDC)	27	28	27	26.5	26.5	24.5
NO2/NO Fraction	0.013622421	0.550401758	0.49092473	0.013487119	0.023691323	0.010273567
BSEC (kJ/kW-hr)	9182	9729	9152	9725	9725	9058
BSFC (g/kW-hr)	242.144	242.575	239.733	227.231	241.797	235.420
BMEP (kPa)	1407.807435	1408.745223	1408.557666	1409.307896	1407.619878	1407.43232

Figure C14. Calterm Parameters

Date Sampled	1/12/2017	1/12/2017	1/13/2017	1/13/2017	1/13/2017	1/13/2017	1/13/2017
Fuel Composition	DF: 200 proof	DF: 200 proof	DF: 190 proof	DF: 190 proof	DF: 190 proof	DF: 190 proof	DF: E85
Engine Speed (rpm)	2447	2449	1813	1813	2436	2473	1805
Engine Torque (N-m)	496.8	251.1	751.1	751.1	497.9	251.3	750.6
Engine Power (kW)	127.3045153	64.39672023	142.6014092	142.6014092	127.0128501	65.07959717	141.8776601
Test Number	15 - Post-AT	16 - Post-AT	17 - Post-AT	19 - Post-AT	20 - Post-AT	21 - Post-AT	22 - Post-AT
Calterm Parameters Cont.							
CBR_Main_SOI (deg BTDC)	0.8	2.5	0.2	0.1	0.4	2.5	0.2
CBP_Air_Fuel Ratio	42.5	46.4	23.1	27.5	39.5	47.0	22.7
EGR_Flow (kg/min)	3.3	3.2	2.6	1.7	3.4	3.3	2.6
EGR_Position (%)	100.5	33.8	45.3	101.6	100.0	35.1	16.2
Exhaust Flow (kg/min)	12.5	9.4	10.4	11.0	12.8	9.7	10.8
Filtrered Turbo Speed (kRPM)	107.9	92.5	107.9	105.4	109.2	93.3	112.3
Charge Flow (kg/min)	15.5	12.4	12.6	12.3	15.9	12.8	13.0
Exhaust Pressure (kPa)	242.1	236.6	266.1	228.2	250.7	238.8	340.3
DOC Inlet Temp (Deg C)	366.8	304.4	443.7	425.5	363.6	300.7	457.5
DOC Outlet Temp (Deg C)	407.1	362.5	446.4	433.0	397.3	357.3	458.6
DOC Delta Temp (Deg C)	40.3	58.1	2.6	7.5	33.7	56.6	1.2
SCR Inlet Temp (Deg C)	392.7	347.6	427.1	413.8	383.5	343.1	439.6
SCR Outlet Temp (Deg C)	393.7	348.3	425.4	417.2	383.8	346.9	437.8
AFT Intake NOx (ppm)	151.5	132.8	265.6	554.4	153.3	126.0	243.7
AFT Outlet NOx (ppm)	18.2	23.3	-1.0	0.9	10.8	18.0	0.2
Charge Temp (Deg C)	49.1	53.2	56.7	47.7	52.3	52.2	64.9
Exhaust Temp (Deg C)	366.8	338.7	543.9	489.1	390.5	335.2	569.0
Charge Pressure (kPa)	197.7	162.5	217.2	204.7	204.9	165.1	232.7
EGR Delta Pressure (kPa)	7.5	7.3	4.4	3.0	7.8	7.6	3.8
Compressor Outlet Temp (Deg C)	145.2	116.5	157.0	146.1	148.7	117.5	169.5
AFT DEF Dosing Rate (g/hr)	377.3	255.9	578.0	1250.5	388.1	248.9	560.8
Nox Reduction Efficiency	0.3533756	0.428026759	0.461269336	0.442595915	0.367059394	0.433911008	0.434037359
Ambiet Temperature (Historic Data from CSU Website) (Deg C)	0	0	2	2	2	2	2
Nox Variance	8.52419	8.57559	10.02394	9.75284	9.64405	14.22889	10.69285
Nox % Deviation	31.895%	26.914%	111.183%	91.192%	47.118%	44.123%	97.929%
Calterm BSE Nox Intlet	1.403458003	1.855288975	1.803210616	4.092427164	1.462672354	1.815004758	1.72014428
Calterm BSE Nox Outlet	0.168594439	0.325247885	0.006844569	0.006953244	0.103288601	0.259559207	0.001596168
Other Data							
Maximum Cylinder Temp (K)	1583.435735	1330.155826	1746.910606	1846.92069	1546.197294	1329.26939	1751.243716
Location of Maximum Cylinder Temp (ATDC)	25.5	21.5	27	24.5	25	21.5	28
NO2/NO Fraction	0.249295756	0.299866628	1.743694433	1.044478585	0.327607258	0.291868712	1.544570794
BSEC (kJ/kW-hr)	9821	11976	9230	9072	9985	12357	9750
BSFC (g/kW-hr)	280.905	327.587	230.810	236.767	277.197	339.602	240.649
BMEP (kPa)	931.7862161	470.9571636	1408.745223	1408.745223	933.8493499	471.3322788	1407.807435

Figure C15. Calterm Parameters

Date Sampled	1/13/2017	1/13/2017	1/13/2017	1/13/2017	1/13/2017	1/13/2017	1/13/2017
Fuel Composition	DF: E85	DF: E85	DF: E85	Diesel	Diesel - Repeat	DF: E85	DF: E85
Engine Speed (rpm)	1800	2453	2465	1800	1797	1802	1801
Engine Torque (N-m)	750.5	498	251.3	750.5	750.7	750.7	750.5
Engine Power (kW)	141.4657977	127.9249165	64.86906876	141.4657977	141.2676576	141.6607229	141.5443898
Test Number	23 - Post-AT	24 - Post-AT	25 - Post-AT	26 - Post-AT	27 - Pre-AT	28 - Pre-AT	29 - Pre-AT
Calterm Parameters Cont.							
CBR_Main_SOI (deg BTDC)	0.2	0.7	2.5	2.3	2.2	0.2	0.2
CBP_Air_Fuel Ratio	25.7	40.0	46.9	20.4	20.4	22.7	25.6
EGR_Flow (kg/min)	2.0	3.5	3.3	2.3	2.2	2.6	2.1
EGR_Position (%)	101.6	99.7	34.5	11.9	12.0	16.0	101.4
Exhuast Flow (kg/min)	10.5	12.6	9.6	11.2	11.1	10.7	10.3
Filtrered Turbo Speed (kRPM)	105.2	109.4	93.0	113.7	113.7	112.4	105.3
Charge Flow (kg/min)	12.1	15.8	12.7	13.0	12.9	12.9	12.0
Exhaust Pressure (kPa)	232.5	252.3	239.8	366.7	364.6	341.0	234.6
DOC Inlet Temp (Deg C)	431.5	361.7	302.5	465.7	466.5	461.5	434.2
DOC Outlet Temp (Deg C)	437.8	395.8	359.2	462.9	463.8	463.1	441.0
DOC Delta Temp (Deg C)	6.3	34.0	56.8	-2.9	-2.7	1.6	6.8
SCR Inlet Temp (Deg C)	418.0	382.1	344.5	442.2	442.9	444.1	421.6
SCR Outlet Temp (Deg C)	420.9	382.6	345.4	443.3	444.2	444.2	425.2
AFT Intake NOx (ppm)	495.0	163.6	137.2	408.9	402.7	249.2	463.7
AFT Outlet NOx (ppm)	2.1	13.6	17.7	-0.8	-1.5	0.5	-0.1
Charge Temp (Deg C)	54.0	58.8	55.1	71.6	71.6	68.1	56.3
Exhuast Temp (Deg C)	514.2	393.7	338.2	638.5	636.8	573.5	517.0
Charge Pressure (kPa)	206.4	206.1	165.3	238.8	237.4	233.1	205.6
EGR Delta Pressure (kPa)	3.7	8.0	7.5	3.0	3.0	3.8	3.8
Compressor Outlet Temp (Deg C)	148.2	149.8	117.3	172.6	173.0	170.5	149.3
AFT DEF Dosing Rate (g/hr)	1093.3	412.0	268.1	966.6	947.4	572.5	1018.3
Nox Reduction Efficiency	0.45077747	0.364241783	0.445720829	0.423819358	0.426712776	0.434344666	0.4555264
Ambiet Temperature (Historic Data from CSU Website) (Deg C)	2	2	2	2	2	2	2
Nox Variance	10.04974	10.19458	13.10111	10.61582	14.00340	1.61237	1.19805
Nox % Deviation	82.485%	42.895%	42.574%	107.764%	3.360%	0.651%	0.259%
Calterm BSE Nox Intlet	3.585540059	1.576276341	1.990846325	2.990602149	2.857247642	1.719430247	3.268841134
Calterm BSE Nox Outlet	0.01545914	0.13072788	0.256501734	0.005593427	0.010926864	0.003666262	0.00087261
Other Data							
Maximum Cylinder Temp (K)	1840.445874	1569.586605	1360.55786	1804.257572	1805.25297	1759.56097	1857.816422
Location of Maximum Cylinder Temp (ATDC)	26	26	21	28	26.5	27.5	26.5
NO2/NO Fraction	0.879708161	0.286453961	0.3196473	1.592308249	0.013607529	0.025376259	0.01346423
BSEC (kJ/kW-hr)	9103	9893	12278	9894	9809	9720	9178
BSFC (g/kW-hr)	230.816	268.284	328.421	231.173	229.175	240.186	234.353
BMEP (kPa)	1407.619878	934.0369075	471.3322788	1407.619878	1407.994993	1407.994993	1407.619878

Figure C16. Calterm Parameters

APPENDIX D

BLENDED FUEL ENGINE TESTS

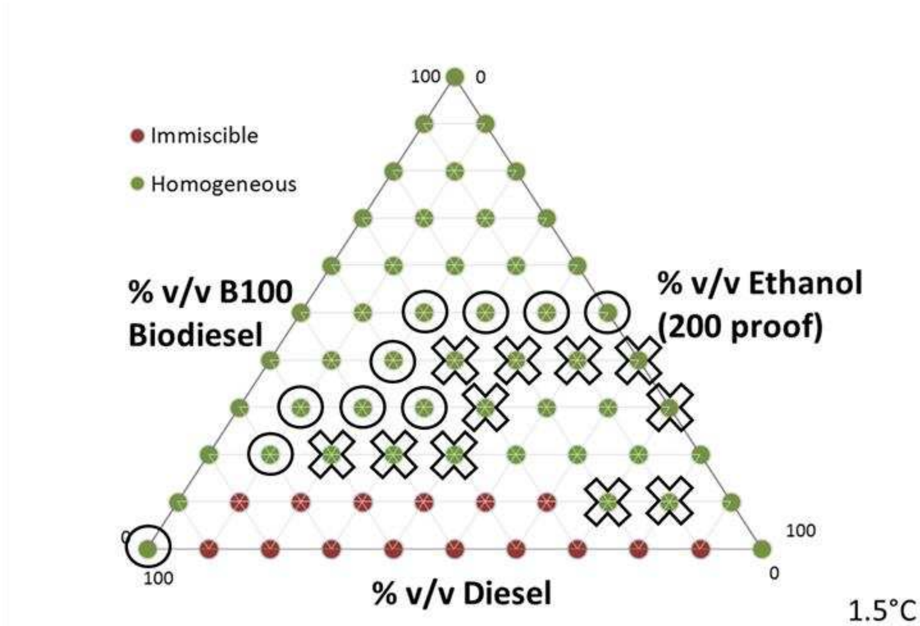


Figure D1. Blended Fuel Test Results. Circled fuels represent fuels that were able to be used in the engine and held a constant speed at 1800 rpm with no load applied. Fuels that have an ‘x’ over them were not able to achieve a stable speed at 1800 rpm with no load applied. Fuels with no mark on them were not tested on this engine.