Development of a Port-Injected Hydrous Ethanol System for Diesel Engines

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Partners:
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Project Objectives:

The purpose of this project was to develop a novel and effective system for operating a diesel engine in a dual fuel mode with hydrous ethanol as the primary fuel. The project sought to prove the hypothesis that using timed injection of denatured 180 proof hydrous ethanol near the intake port as opposed to continuous fumigation in the intake plumbing allows higher fumigant energy fraction (FEF) levels than are possible with currently marketed systems while reducing emissions and improving engine fuel efficiency. FEF is defined as the energy content of the hydrous ethanol divided by the total fuel energy content. Our objectives included developing a hydrous ethanol port fuel injection (PFI) system applicable for a range of aftermarket applications and engine type. By developing a stand-alone fuel ethanol fuel injection system, we envisioned no modification of the existing engine control unit (ECU). In other applications like in reactivity controlled compression ignition (RCCI) combustion, the stock ECU is replaced or reprogrammed to further increase engine efficiency, a scenario that could be possible in collaboration with an industrial partner like Cummins Inc.

Our objectives during the project were to: 1) develop a hydrous ethanol injection strategy using a representative industrial diesel engine in the laboratory with a programmable control system, 2) design a portable controller for use in field applications, 3) determine an appropriate field demonstration site and use laboratory results to raise additional funding for installation of the developed hydrous ethanol system.

Description of Work Performed:

Benchmarking Existing Hydrous Ethanol Injection System

One of the project objectives was to determine whether hydrous ethanol PFI could enable higher FEF than fumigation systems. To evaluate this, a commercially available injection system developed by CleanFlex LLC was installed and tested to provide baseline data. Initial work was done as a collaborative effort between CleanFlex engineers and UMN researchers.

Figure 1 shows an illustration of the injection system as installed on a John Deere 4045HF475 test engine in the engine research laboratory at University of Minnesota. The custom injector body was mounted in-line approximately 1 foot upstream of the intake manifold and downstream of the charge-air cooler. Two automotive grade injectors were used to inject 120 proof hydrous ethanol into the intake air plumbing according to CleanFlex recommendations. Injectors were positioned at an angle relative to intake airflow to promote mixing between hydrous ethanol and air prior to entering the intake manifold.

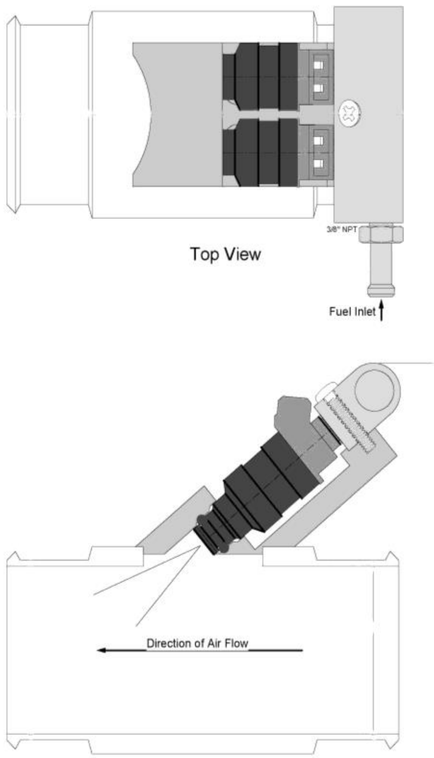

Figure 1: Top and side view of the injector body provided by CleanFlex LLC

The timing and hydrous ethanol injection rate was controlled by a fuel system separate from the engine ECU. A Hall Effect sensor and manifold air pressure (MAP) sensor were installed on the engine as part of the system to provide an estimation of air flow and engine speed for calculating the pulse rate and duration of the fumigation injectors. Data was collected for both hydrous ethanol fumigation and diesel only combustion modes. A modified ISO 8178 off-road vehicle testing cycle was used for all testing in the culmination of all three studies conducted, shown in Table 1. The engine was operated with and without fumigation of 120 proof hydrous ethanol.

Table 1: Modified ISO 8178 engine operation conditions

Mode	Engine Speed (RPM)	Engine Load (N-m)
1	2400	450
2	2400	350
3	2400	250
4	2400	50
5	1400	450
6	1400	350
7	1400	250
8	1000	0 (idle)

The CleanFlex fumigation system was operated according to the manufacturer's settings at each test mode. It was found that the FEF varied linearly with intake manifold pressure over the eight operating modes as shown in Figure 2. Over the eight operating modes, the addition of hydrous ethanol had little to no effect on engine efficiency, with a minimal decrease (<1%) in combustion efficiency (CE). Brake specific fuel consumption (BSFC) was higher at all test modes, due to the lower calorific value of ethanol as compared to diesel fuel. This is validated as the brake thermal efficiency (BTE) is similar between hydrous ethanol fumigation and conventional diesel combustion.

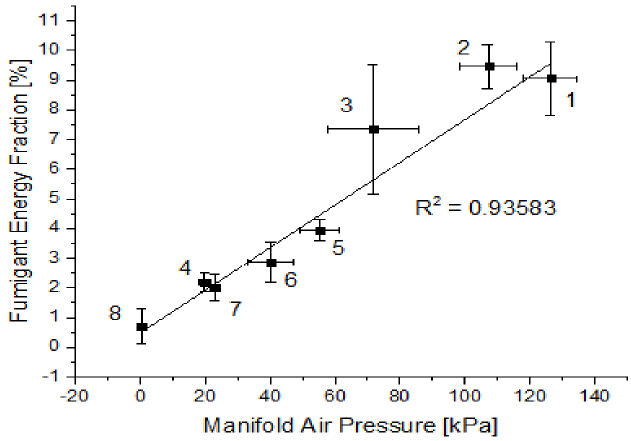

Figure 2: Fumigant energy fraction as a function of intake manifold pressure

Figures 3-8 present the effect of fumigation on select brake specific engine-out emissions per testing mode. It can be seen that although fumigation with 120 proof hydrous ethanol effectively reduces NO, it also increases NO_2, leading to little to no effect on NO_X. The reduction of NO is a function of charge-cooling due to hydrous ethanol vaporization along with the added heat capacity of the mixture from dilution with water. Both of these effects lower combustion temperatures, reducing thermal NO production through the Zel'dovich mechanism; however, NO_2 formation is more favored under these conditions. The decrease in combustion temperatures also causes incomplete combustion, and increased CO emissions due to incomplete oxidation of CO to CO_2, and increased THC emissions. We also see a significant amount of unburned ethanol in the exhaust, further indicating incomplete combustion. Lower in-cylinder temperatures are beneficial to prevent soot formation, which was observed in testing.

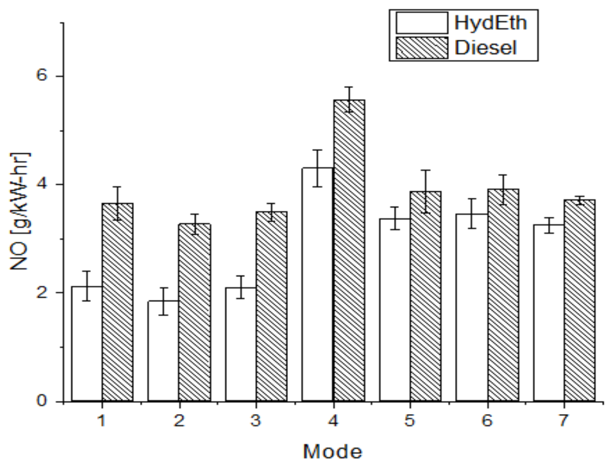

Figure 3: NO emissions as a function of mode with and without fumigation

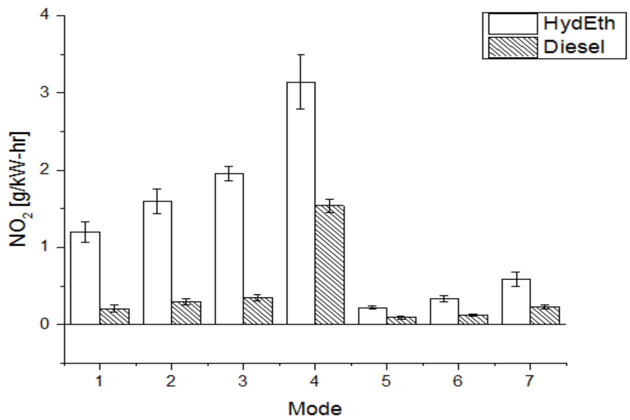

Figure 4: NO_2 emissions as a function of mode with and without fumigation

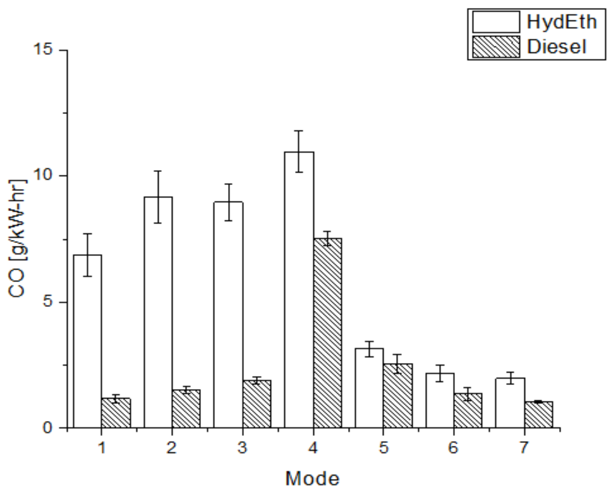

Figure 5: Brake specific CO emissions as a function of operating mode with and without fumigation

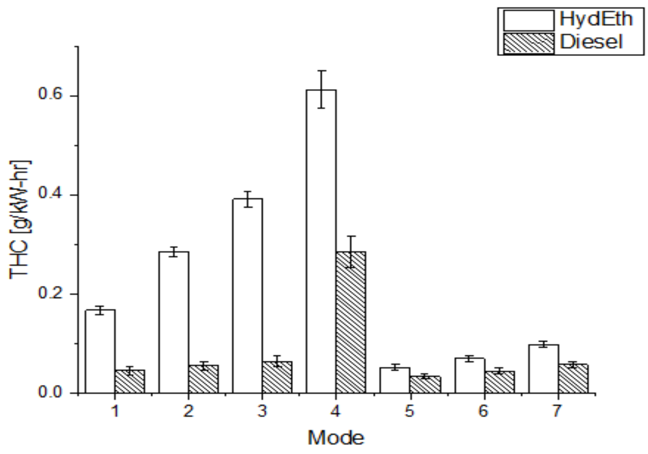

Figure 6: Brake specific non-oxygenated total hydrocarbon emissions as a function of engine operating mode.

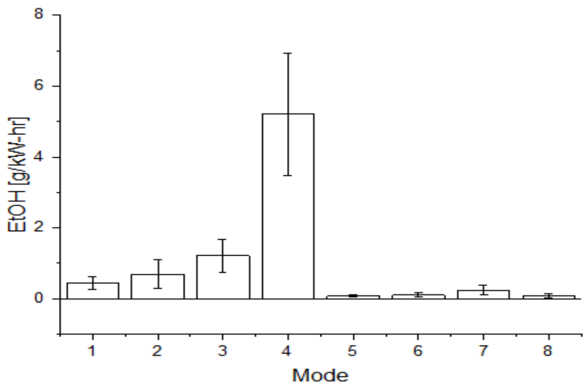

Figure 7: Brake specific ethanol emissions as a function of operating mode for fumigation cases.

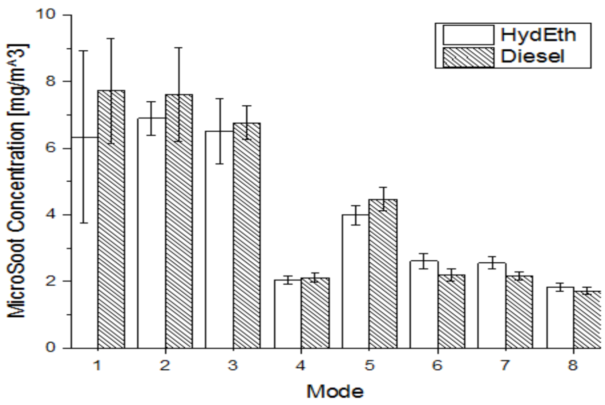

Figure 8: Concentration of soot as a function of operating mode with and without fumigation

Although this study found that fumigation using the CleanFlex system is a viable dual-fuel strategy for diesel engines, the strategy had little to no effect on NOx or soot emissions. Additionally, the CleanFlex system did not allow more than 10% FEF, which will not require very much ethanol to be used and will thus not significantly expand the use of ethanol if implemented widely. A requirement for future systems is to increase the FEF in dual fuel systems for diesel engines.

The results of our study suggest that increasing FEF may also increase the benefits of hydrous ethanol fumigation. Higher FEF levels may be achieved by using hydrous ethanol with lower water content, or through better mixing through injection closer to the intake valves. Due to the limitations created by adding water vapor to engine combustion, lowering the water content of hydrous ethanol would be preferable for lowering in-cylinder temperatures. PFI of hydrous ethanol would also provide controllability of injection rates and durations, allowing for higher FEF levels without condensation in the intake manifold. Furthermore, increased preheating of the fumigant fuel could result in more complete vaporization, increasing in-cylinder temperatures for higher combustion efficiency.

Heated Hydrous Ethanol PFI System – Phase 1

Using the baseline information learned from the Cleanflex experiments, a new hydrous ethanol PFI system was developed for the test engine. Experiments were conducted with the new system to gain additional understanding of the effect of dual-fuel strategies on engine performance and emissions. The same John Deere 4045 test engine was fully instrumented and equipped with a fueling system designed to fit onto the intake manifold of the engine, seen in Figure 9.

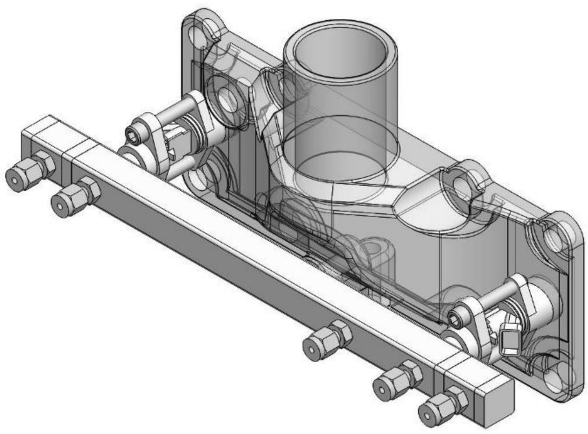

Figure 9: Isometric view of novel hydrous ethanol PFI system

Based on the Cleanflex data, it was hypothesized that pre-heating the hydrous ethanol prior to port injection would enhance vaporization and lead to lower levels of unburned ethanol emissions from the engine. To test this, a novel integrated heat exchanger-fuel rail was developed as shown in Figure 10. Engine coolant circulated in three tubes mounted inside a larger tube that contained hydrous ethanol. The heat exchanger effectiveness was evaluated using an ANSYS finite element analysis.

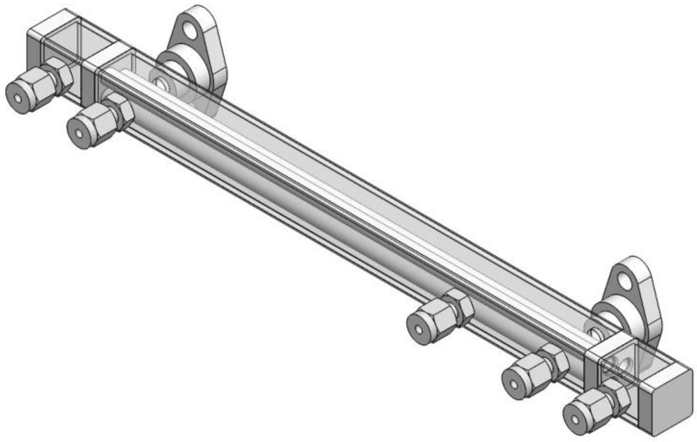

Figure 10. Integrated hydrous ethanol fuel rail heat exchanger

The engine was operated at each mode for heated and unheated 180 proof hydrous ethanol, and diesel only operation. There were no modifications made to the engine ECU; diesel flow rate was controlled via engine throttle to maintain engine speed and load at the correct conditions when hydrous ethanol was being injected. Figure 11 depicts the maximum FEF achieved for heated and unheated ethanol injection where injector limitations did not allow for high FEF at high speed and load cases. Engine knock, or pre-ignition of the ethanol in the cylinder occurred at low FEF for the low speed engine modes. This is due to sufficient time for autoignition of ethanol to occur at high cylinder pressure can only be alleviated by reducing engine compression ratio, turbocharger boost or intake manifold temperature. Overall, the designed PFI system achieved FEF levels 2-3 times higher than the CleanFlex system, significantly improving the amount of diesel fuel displaced with no impact on engine performance.

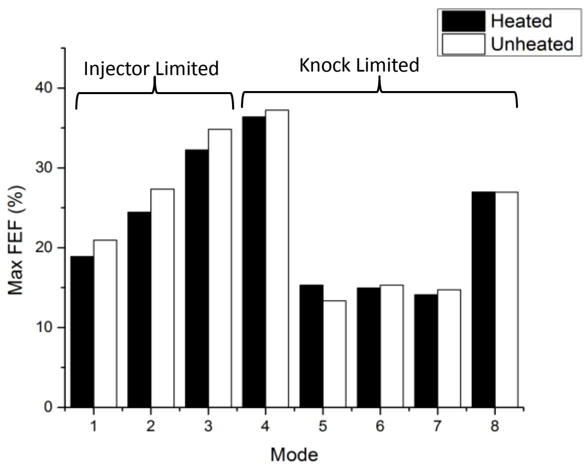

Figure 11: Maximum FEF achieved for each test mode for heated and unheated ethanol injection

Figures 12-17 depict the effect of hydrous ethanol PFI on select engine out emissions as a function of FEF for the previously stated eight-mode test. The horizontal line in each plot represents diesel only operation with 0% FEF. Similar to the fumigation study, NO emissions decrease with increasing FEF, but NO_2 increases, causing no change in NO_X emissions. In addition, no discernible change was noticed between heated and unheated hydrous ethanol. CO, ETOH, and THC emissions increased significantly with increasing FEF, which can be explained by the charge cooling effects of the increasing amount of water being injected with increasing FEF. Soot emissions however begin to increase before decreasing with increasing FEF. The decrease in soot can be attributed to increased unburned ethanol in the exhaust, increasing the concentration of OH radicals, which is known to oxidize soot particles. Soot also decreases at high FEF due to reduced equivalence ratio in the diesel flame.

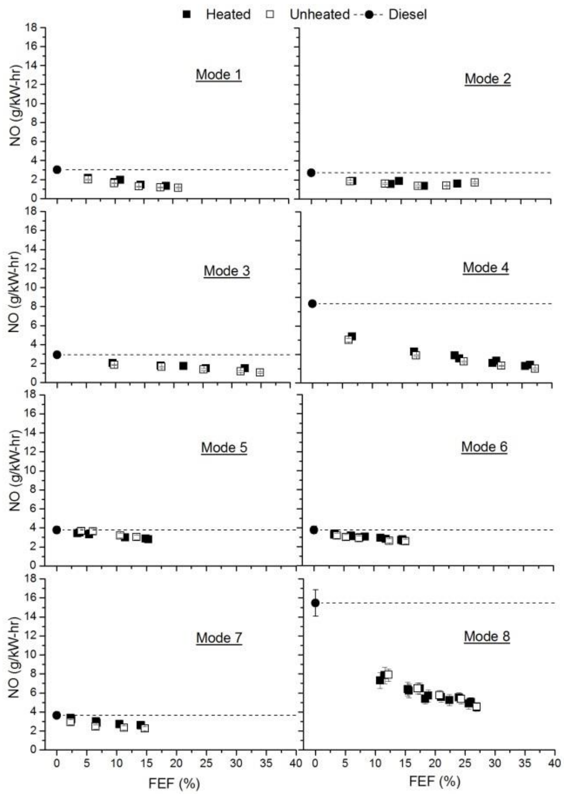

Figure 12: Brake-specific NO emissions as measured by FT-IR in g/kW-hr for each mode as a function of FEF

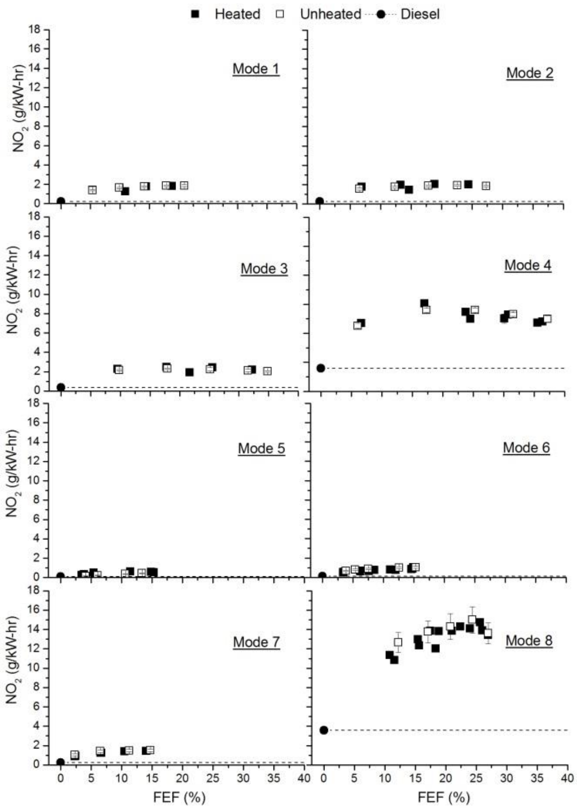

Figure 13: Brake-specific NO_2 emissions as measured by FT-IR in g/kW-hr for each mode as a function of FEF

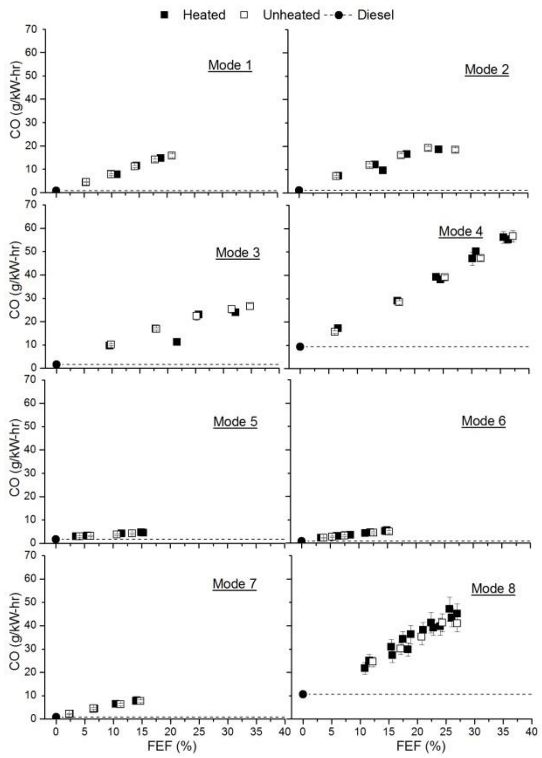

Figure 14: Brake-specific CO emissions as measured by FT-IR in g/kW-hr for each mode as a function of FEF

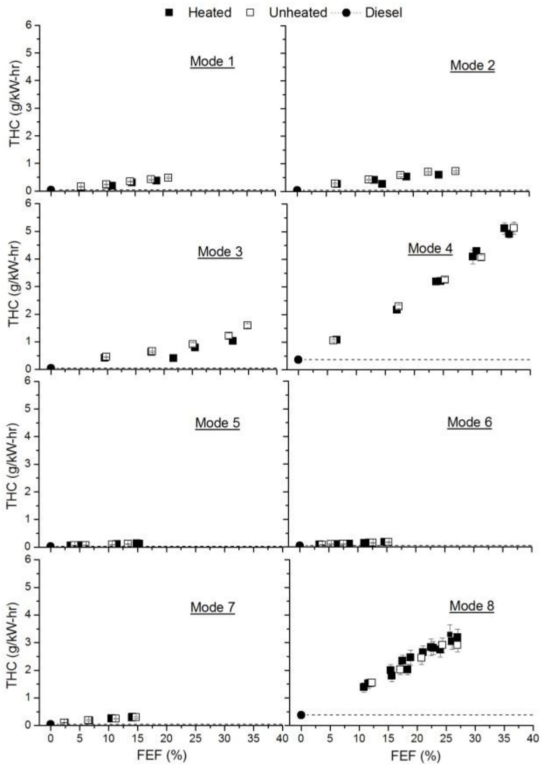

Figure 15: Brake-specific THC emissions as measured by FT-IR in g/kW-hr for each mode as a function of FEF

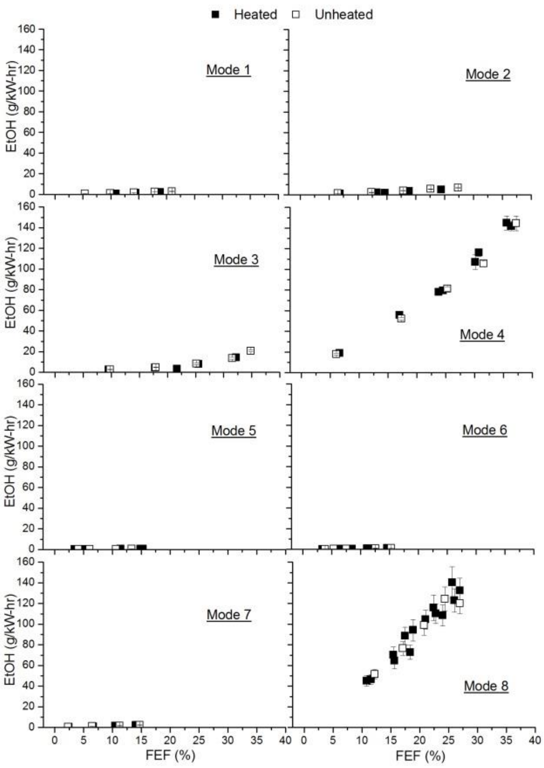

Figure 16: Brake-specific EtOH emissions as measured by FT-IR in g/kW-hr for each mode as a function of FEF

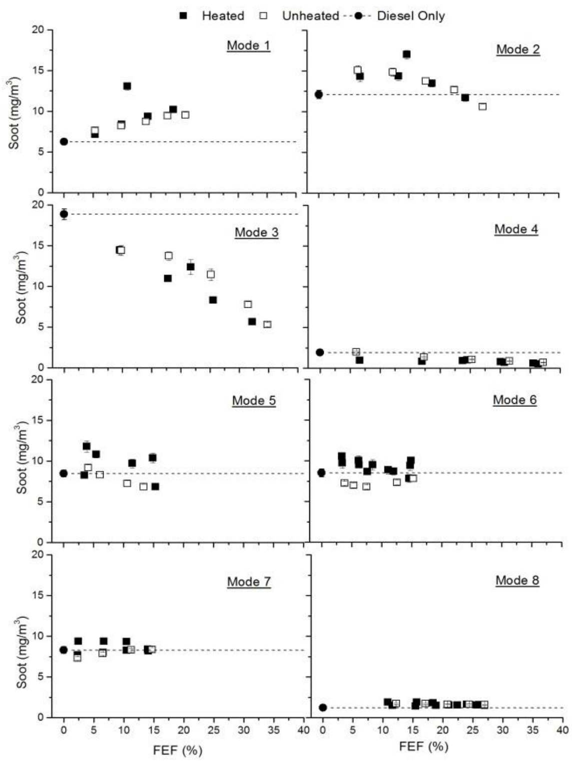

Figure 17: Soot concentration as measured by Microsoot in mg/m^3 for each mode as a function of FEF

Like fumigation, PFI dual-fuel operation is a feasible method for introducing a secondary fuel like hydrous ethanol into diesel engines. However, PFI of 180 proof hydrous ethanol does not impact NO_X emissions overall, while increasing CO, THC, and unburned ethanol emissions. In addition, it was found that preheating the hydrous ethanol prior to injection had no effect on engine performance and emissions. The work suggests that decreasing hydrous ethanol proof, and increasing maximum injector flow rates may result in more favorable conditions for emissions reductions.

Novel Hydrous Ethanol PFI System – Phase 2

Phase 2 of the PFI system study involved equipping the novel PFI system with injectors rated at three times the flow rate and testing two different hydrous ethanol blends, 180 proof and 160 proof. This was done to examine the impact of water content on engine performance and emissions. The same test engine and experimental procedure as Phase 1 was followed in Phase 2. Figure 18 depicts the maximum FEF achieved at each mode with 160 and 180 proof hydrous ethanol. With higher flow injectors, all testing conditions were knock-limited, meaning that audible engine knock occurred before injector pulse width limitations were reached. A peak FEF greater than 60% was attained at high load and speed operation attaining one of the goals of the project. Low speed, high load operation resulted in similar knock limited FEF than Phase 1. These results indicate that practical hydrous ethanol PFI systems could achieve the maximum diesel replacement benefit in applications where engines are operated at high speed and load.

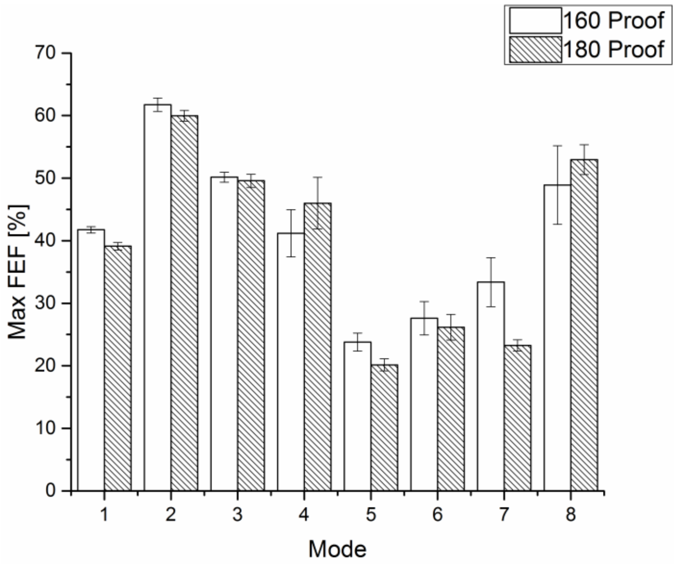

Figure 18: Maximum FEF achieved at each test mode

Figures 19-23 depict the effect of hydrous ethanol PFI on selected engine out emissions as a function of FEF for all eight testing modes. The horizontal line represents diesel only operation with 0% FEF. Similar to previous work, NO emissions decrease with increasing FEF while NO_2 increases. However, at high FEF NO_2 actually begins to decrease, resulting in a reduction in NO_X emissions. The NO_X emissions results indicate a fundamental deficiency of aftermarket dual fuel systems. NO_2 is more acutely toxic than NO and future regulations may limit the proportion of NO_2/NO_X that engines can emit. Results indicate that NO formation is unchanged from diesel only operation and that NO to NO_2 conversion is occurring in the expansion stroke, aided by high in-cylinder unburned ethanol concentrations. Additional research has been completed at University of Minnesota to determine the chemical mechanism for ethanol-assisted NO to NO_2 conversion in dual fuel modes.

Carbon monoxide (CO) emissions appear to reach a horizontal asymptote at high FEF, while unburned ethanol rises monotonically. Soot formation follows a similar trend as the in the Phase 1 study where increasing FEF reduced combustion temperatures, and increased equivalence ratio, bringing the combustion zone further into the soot formation zone. As FEF increased, combustion temperatures decreased further until combustion was outside of the soot formation zone. As shown in the Phase 1 work, dual fuel operation results in negligible reductions in NO_X and only slight reduction in soot emissions at high FEF.

Water content in the hydrous ethanol had a minimal impact on emissions. However, lower ethanol proof had a detrimental effect on engine efficiency at high FEF (not shown). Given that 160 proof hydrous did not have knock inhibition benefits as shown in Figure 18, the experiments illustrated that 180 proof hydrous ethanol is preferred for dual fuel operation.

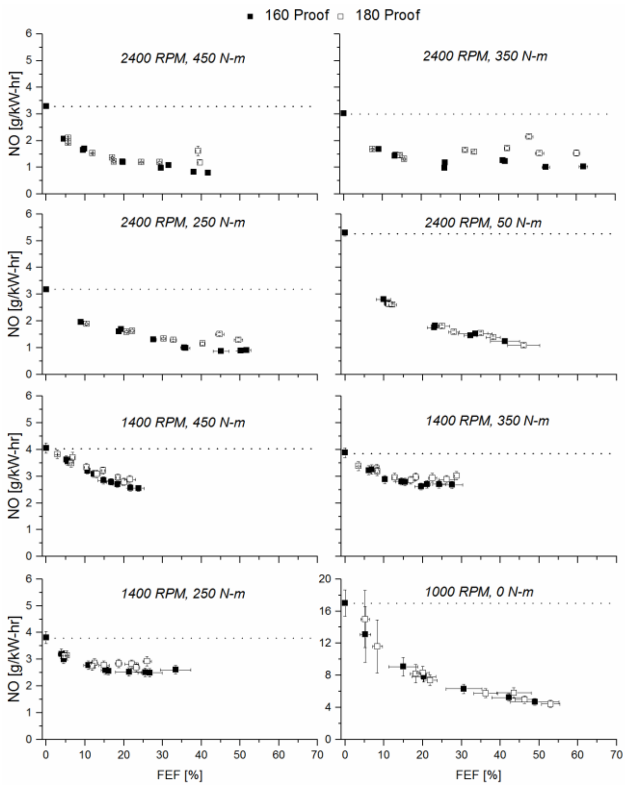

Figure 19: Brake specific NO emissions as a function of FEF for 160 and 180 proof hydrous ethanol

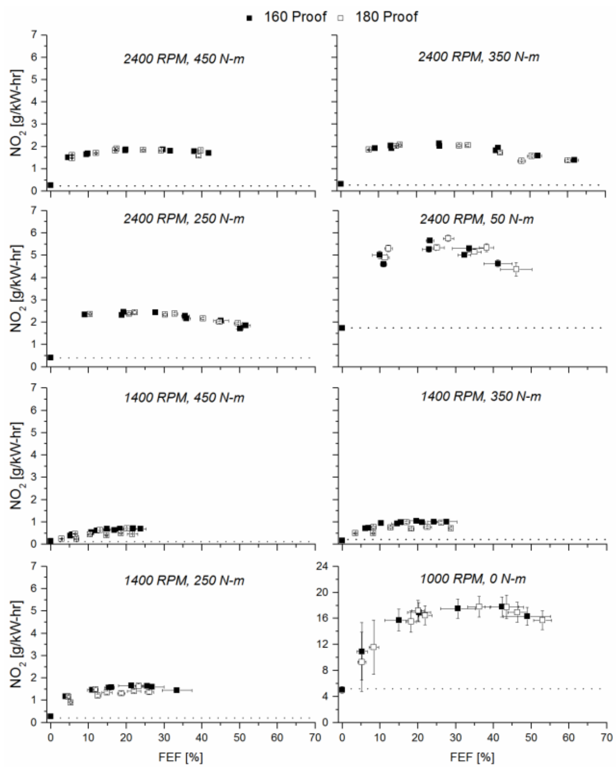

Figure 20: Brake specific NO_2 emissions as a function of FEF for 160 and 180 proof hydrous ethanol

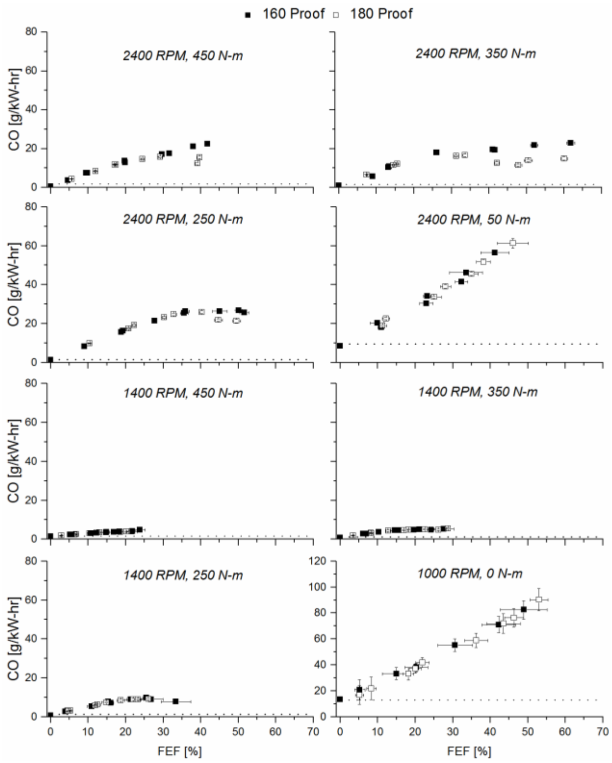

Figure 21: Brake specific CO emissions as a function of FEF for 160 and 180 proof hydrous ethanol

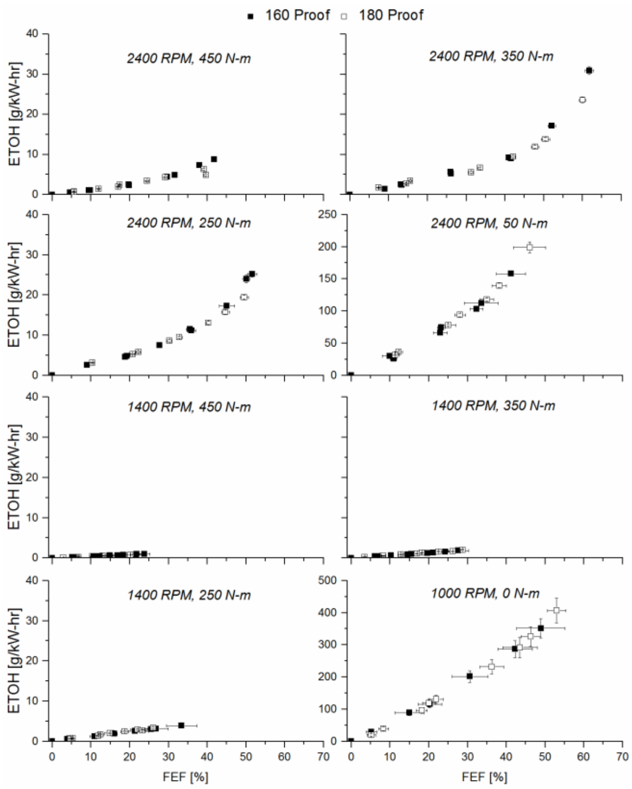

Figure 22: Brake specific unburned ethanol emissions as a function of FEF for 160 and 180 proof hydrous ethanol

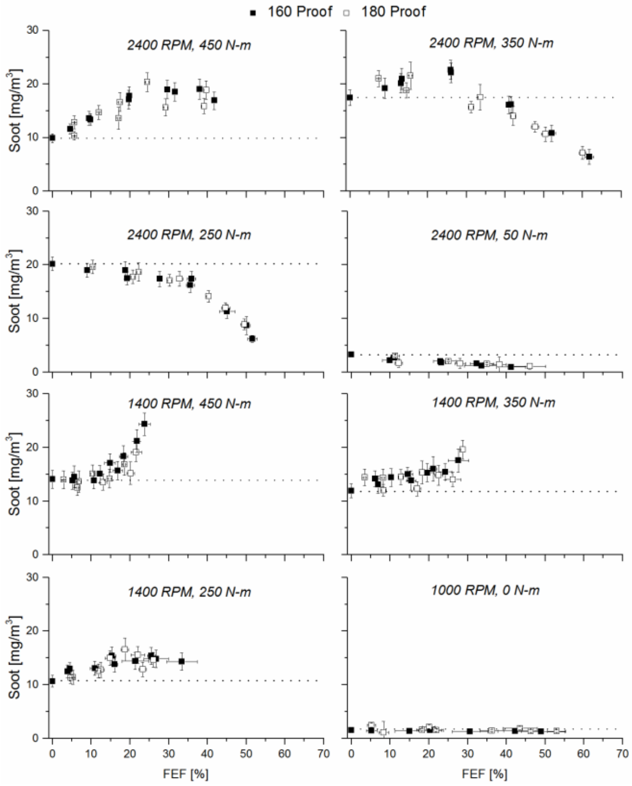

Figure 23: Soot concentration as a function of FEF for 160 and 180 proof hydrous ethanol

Similar to the previous two studies, PFI dual-fuel operation with 160 and 180 proof hydrous ethanol yielded no benefits to soot and NO_X emissions overall, while increasing CO, HC, and unburned ethanol emissions. The results of the culmination of all three studies suggests that aftermarket dual fuel systems using hydrous ethanol and diesel fuel cannot achieve the same drastic reductions in emissions as advanced combustion modes that control diesel injection parameters.

Results of Technology or Process Assessed:

The results of the technology developed in this project are as follows: 1) The developed hydrous ethanol dual fuel PFI system can achieve 60% diesel replacement by energy (FEF) at high engine load and speed without modification to the diesel fuel injection control system, a significant improvement over existing commercial systems. 2) Low engine speeds and high engine load operation has limited FEF due to knocking. 3) Emissions of NO_X and soot decrease only at very high FEF and benefits are not sufficient to eliminate the need for aftertreatment systems to achieve regulated standards. 4) Where NO_X emissions are largely unchanged from diesel-only operation, dual fuel operation results in higher NO_2/NO_X ratio that has negative implications for human health and for meeting regulatory compliance. 5) Preheating of ethanol prior to injection has minimal impact on engine performance or emissions. 6) Dual fuel operation is best suited using 180 proof ethanol to achieve high FEF without reductions in engine thermal efficiency. 7) Additional interventions are required to reduce NO_X and soot emissions from diesel engines using dual fuel hydrous ethanol systems.

Benefit to Minnesota Economic Development:

This project has shown that hydrous ethanol can be effectively used in diesel engines without changing stock engine control. The developed dual fuel system allows up to 60% diesel replacement by energy. Although emissions reductions have not yet been realized, the developed system could be implemented in existing engines used in the agricultural sector. Minnesota is a large corn-based ethanol producer and could benefit by expanding the ethanol market by replacing diesel fuel. An economic evaluation should be completed to quantify the exact benefits that could be gained from using ethanol in diesel engines as a function of fuel price.

Marketing:

The following technical papers have been published regarding the work completed in this project:

1. Hwang, J., Nord, A. and Northrop, W. (submitted) Efficacy of Add-On Hydrous Ethanol Dual Fuel Systems to Reduce NOx Emissions from Diesel Emissions. *ASME IC Engine Division Fall Technical Conference,* Greenville, SC, ICEF2016-9349.
2. Nord, A., Hwang, J., and Northrop, W. (2015) Emissions from a Diesel Engine Operating in a Dual-Fuel Mode Using Port-Fuel Injection of Heated Hydrous Ethanol, *ASME IC Engine Division Fall Technical Conference,* Houston, TX, ICEF2015-1067.
3. Hwang, J. and Northrop, W. (2014). Gas and Particle Emissions from a Diesel Engine Operating in a Dual-Fuel Mode using High Water Content Hydrous Ethanol. *ASME IC Engine Division Fall Technical Conference,* Columbus, IN, ICEF2014-5460.

Discussions with ethanol plant manufacturers and engine manufacturers have also resulted from this project. Marketing activities are expected to assist in applying for additional funding to continue this research.

Conclusions:

Based on the work conducted in this project, we conclude that an aftermarket PFI-based dual fuel system could be safely used in diesel engines to offset the use of diesel fuel with 180 proof hydrous ethanol. This system reaches higher diesel replacement than currently available commercial systems. While this system would not significantly reduce soot and NO_X emissions compared to diesel-only operation, it could have the benefit of offsetting fuel costs depending on the relative price of ethanol and diesel fuel.

Future Needs/Plans:

One key market driver for dual fuel systems is to use them as an alternative to add-on catalytic aftertreatment systems for off-highway engines meeting the California Air Resources Board (CARB) Diesel Risk Reduction Plan verification levels for in-use engines. An extension of this project has been proposed to develop an aftermarket hydrous ethanol reforming system that would meet CARB in-use standards for both PM and NO_X, an achievement that has not been achieved by any dual fuel ethanol systems to date. In the proposed work, we will develop a thermally integrated system that uses exhaust heat to reform hydrous ethanol into a mixture of hydrogen and carbon monoxide to reduce combustion temperatures and thus reduce NO_X formation in the engine.

Another area of future work will examine the potential for commercialization of the PFI system developed in this project. Funding for a demonstration platform, potentially a diesel-powered irrigation pump is currently being pursued.