High efficiency enabled by hydrous ethanol use in dual-fuel engines

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Project Objectives:

The purpose of this project is to use hydrous ethanol to demonstrate high efficiency with reduced emissions in a modified diesel engine where ethanol provides up to 80% of the fuel energy input. Our approach improves on traditional ethanol fumigation in diesel engines and opens up new applications for ethanol as a diesel fuel replacement. A key motivation for this work is previous research that suggests hydrous ethanol is less expensive to produce than anhydrous ethanol and more renewable due to lower fossil energy consumption[1,2,3]. Eliminating dehydration and limiting distillation can save considerable energy in production and increases the sustainability of the overall process. Greater use of hydrous ethanol will improve both the economics and life cycle analysis of ethanol.

This project is also motivated by the desire to expand the market for fuel ethanol. The State of Minnesota consumed 941million gallons of diesel fuel in 2009, with the majority used in on-highway applications (16% used in agriculture). Hypothetically, if 10% of that amount were replaced with ethanol, it would consume approximately 0.9% of the US installed Ethanol production capacity. With increasing diesel market price, motivation for replacement with ethanol, especially in the U.S. Midwest, is strong. Manufacturers are starting to recognize that ethanol can be an effective diesel alternative as evidenced by Cummins Inc. which has announced a 2.8L high output spark ignition engine that operates solely on E85[4]. Dual fuel strategies using ethanol and diesel are also attractive. Also known as fumigation, the concept involves injection of ethanol in the intake manifold and direct injection of diesel fuel into the cylinder as shown in Figure 1.

Hydrous ethanol has advantages when used in dual-fuel diesel engines. Previous work has shown potential to reduce regulated diesel exhaust emissions such as oxides of nitrogen (NOx) and particulate matter (PM). Depending upon the type and extent of reduction, advanced emission control technology, such as diesel particulate filters and selective catalytic reduction using urea, may not be required to meet the off-road regulations. Eliminating the requirement for aftertreatment devices reduces capital equipment and maintenance costs. In this project, a new dual-fuel combustion mode, reactivity controlled compression ignition (RCCI) is used to reduce soot and oxides of nitrogen (NO_x) emissions while maintaining very high engine efficiency. In RCCI, a less reactive fuel like ethanol is injected into the intake port and diesel fuel is injected directly into the cylinder.

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[1] Martinez-Frias, J., Aceves, S. M. & Flowers, D. L. Improving Ethanol Life Cycle Energy Efficiency by Direct Utilization of Wet Ethanol in HCCI Engines. J. Energy Resour. Technol. 129, 332 (2007).
[2] Shapouri, H., et al. The energy balance of corn ethanol revisited. Transactions of ASAE 46(4):959-968 (2003).
[3] Shapouri, H., et al. Estimating the net energy balance of corn ethanol. USDA Economic Research Service (1995).
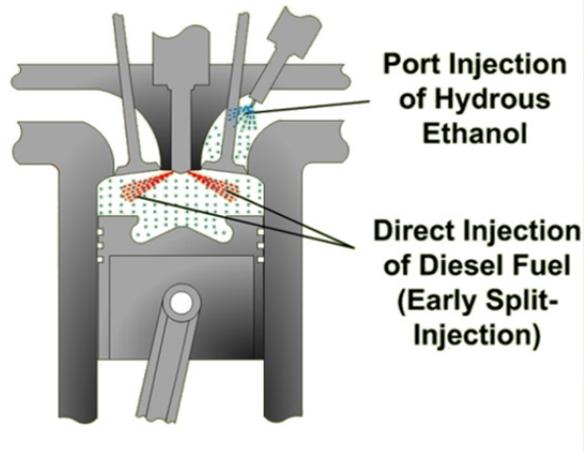[4] http://cumminsengines.com/cummins-ethos-28l-engine-demonstrates-50

Figure 1: Illustration of dual-fuel injection system used in this project

Compared with traditional fumigation where diesel fuel is injected close to the top of the compression stroke, RCCI uses very early direct injection of diesel to create a primarily premixed fuel and air mixture. The amount and timing of the diesel injection controls ignition enabling combustion to proceed without fuel-rich or high temperature zones thus mitigating pollutant formation. Premixed combustion also allows for thermodynamically optimal operation which has shown to improve efficiency of diesel engines.

The originally stated project objectives are as follows:

1) Examine RCCI operation with hydrous ethanol a single cylinder research engine to optimize engine efficiency while maintaining low engine out NO_X and soot emissions. DOE methodology will be used to explore the widest possible range possible.
2) Gather and analyze resulting data from single-cylinder testing in a sensitivity matrix to show the feasible operating range for a hydrous ethanol fueled RCCI combustion mode regime.
3) Experimentally verify the performance and emissions improvements in a full-scale multi-cylinder diesel engine modified for RCCI operation with hydrous ethanol as the primary fuel.
4) Recommend applications for the practical use of hydrous ethanol in diesel engines operating in the RCCI mode.

Description of Work Performed:

A single-cylinder test engine setup was prepared for hydrous ethanol RCCI operation. The engine used in this study was a modified four-cylinder Isuzu commercial engine converted to single cylinder use. It was fully instrumented and equipped with a port fuel injection system for ethanol. The single-cylinder engine test stand was modified to accommodate increasing cylinder pressure, intake heating and exhaust gas recirculation (EGR). This was accomplished by connecting the engine to the university's clean and dry compressed air system and by plumbing an EGR line with a cooler. A hot-air mass flow meter, expansion tank for dampening out engine pulsations and a resistive air heater were also installed. A photo of the modified engine setup is shown in Figure 2.
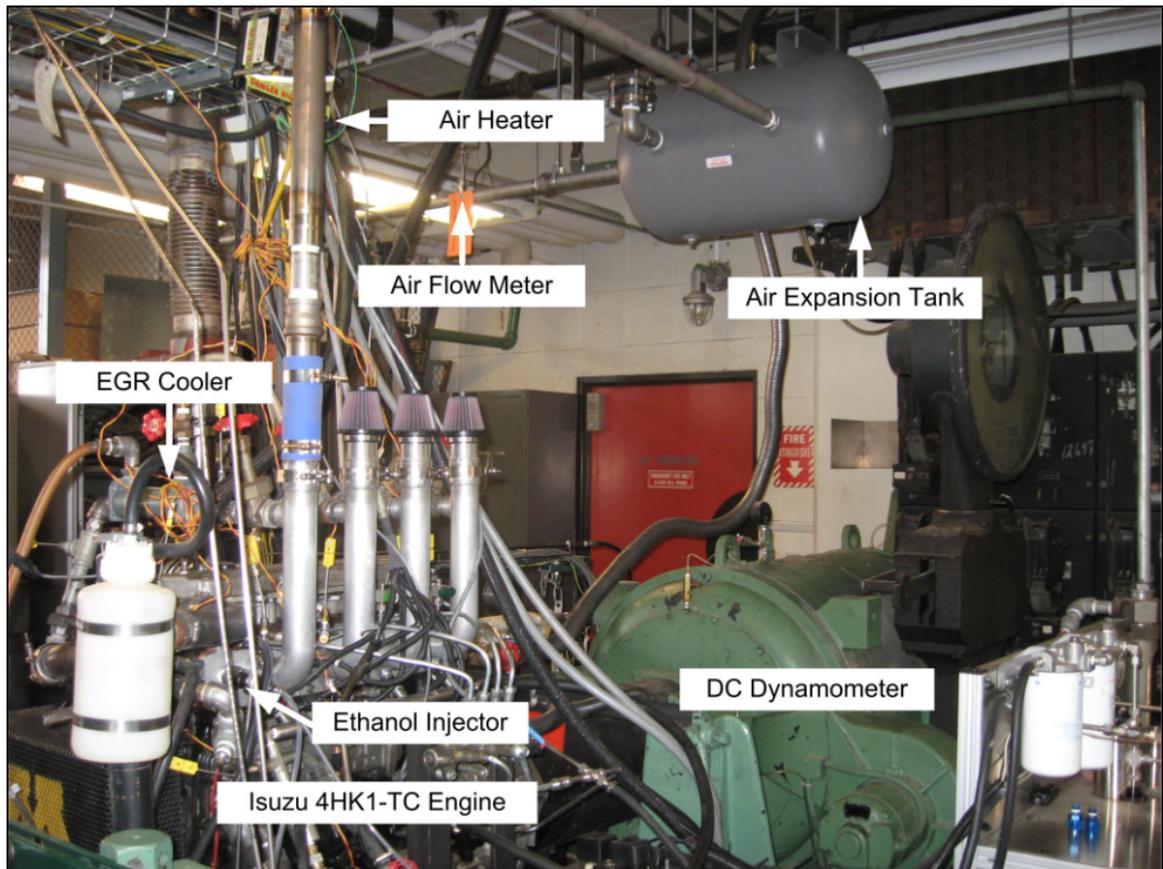
Figure 2: Modified single cylinder engine test stand including plumbed compressed air line, expansion tank, air heater and EGR system.

To evaluate single-cylinder RCCI operation, engine load was swept over the range from 10 to 35 indicated HP/cylinder, with some operating parameters held constant, as shown in Table 1. We have found that increased intake pressure allows sufficient air to enter the cylinder at higher loads while using EGR dampens excessive peak cylinder pressure. Increased intake manifold temperature is necessary to increase the reactivity of hydrous ethanol such that ignition can occur at lower loads. Intake pressure, EGR and intake manifold temperature were changed with engine load setting. The test matrix of parameters that were varied during the RCCI evaluation is shown in Table 2.

Table 1: The parameters held constant during the RCCI evaluation. The engine was operated with two-step split diesel injection

	Units	Parameter
Speed	rpm	1500
1st diesel injection timing	°BTDC	60
% of diesel in 1st injection	%	60
Ethanol in water	% b.v.	75
Diesel energy fraction	% LHV	25
Coolant temperature	°C	85

Table 2: Parameters varied during the RCCI evaluation

	Units	Range
Indicated power*	HP/cyl	10 - 35
2nd diesel injection timing	° BTDC	40 - 25
Diesel injection pressure	bar	400 - 800
EGR	%	0 - 35
Intake pressure	kPa	0 - 230
Intake temperature	°C	40 - 100

as measured by in-cylinder pressure data

The following describes selected results of testing the engine using 150 proof ethanol (75% ethanol in water) over the engine load range from 10 to 35 hp/cylinder. A constant diesel energy fraction of 25% based on lower heating value was used. Figure 2-3 shows the indicated specific (IS) NO_X, soot, non-methane hydrocarbons (NMHC) and carbon monoxide (CO) emissions results as a function of the timing of the second diesel fuel injection (the first injection is held constant). These were calculated based on measured concentrations in the exhaust and indicated power output of the engine as calculated from in-cylinder pressure measurements. Indicated power reflects the amount of power generated by the engine cycle and does not include friction and auxiliary loads. The first diesel injection timing represented 60% of the diesel fuel input and was timed at 60 ° BTDC. NO_X and soot emissions for hydrous ethanol RCCI remained low up to a load of 34.9 hp/cylinder as shown in Figure 3. For the loads tested, NO_X could be lowered to below the Tier 4 standards with optimized fuel injection timing. Exhaust gas recirculation (EGR) was necessary as engine load increases to lower peak combustion temperatures and keep NO_X emissions low. The RCCI combustion mode was able to almost eliminate smoke emissions from the engine at all loads and injection timing settings as shown in Figure 3. This

result is significant as conventional diesel engines operating with diesel fuel only generally have much higher NO_X and soot concentrations that increase with load. ***Our results show that hydrous ethanol RCCI operation may not require expensive NO_X catalysts or diesel particulate filters (DPFs) to meet the most stringent emissions standards for off-road vehicles.***

Unburned hydrocarbon emissions were approximately 100 times the US EPA Tier 4 off-highway standards as shown in Figure 4. Here the hydrocarbon emissions were dominated by unburned ethanol that escapes the combustion chamber. The RCCI regime is known for high levels of hydrocarbons resulting from cool areas of the combustion chamber where premixed fuel does not ignite. Such emissions must be oxidized using a diesel oxidation catalyst (DOC) for any practical combustion system. The CO emissions were also high for low engine loads as shown in Figure 4 though they can be reduced to levels comparable with the Tier 4 standard for higher loads.
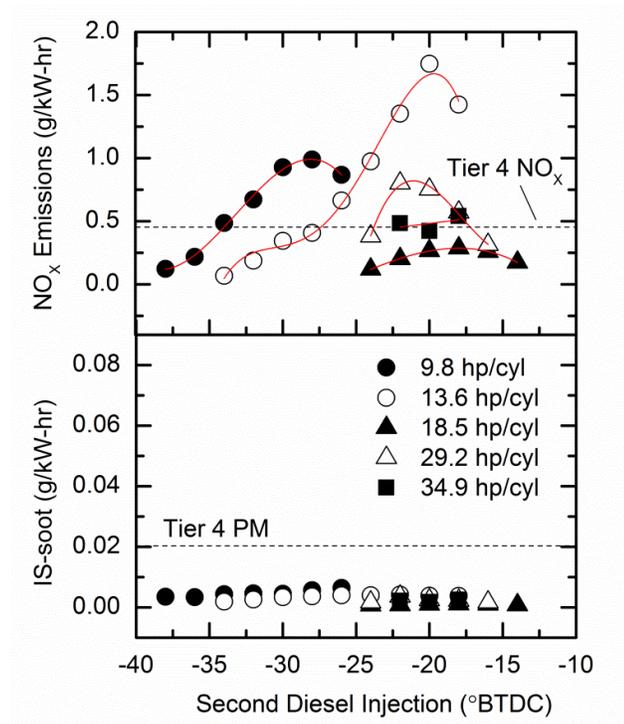

Figure 3: Engine indicated specific (IS) NO_X and soot emissions as a function of 2nd diesel injection timing in the RCCI mode. Engine operating conditions: 150 proof ethanol, engine speed = 1500 rpm, ethanol energy fraction = 75%

Figure 4: Engine indicated specific (IS) CO and non-methane hydrocarbon (NMHC) emissions as a function of 2nd diesel injection timing in the RCCI mode. Engine operating conditions: 150 proof ethanol, engine speed = 1500 rpm, ethanol energy fraction = 75%
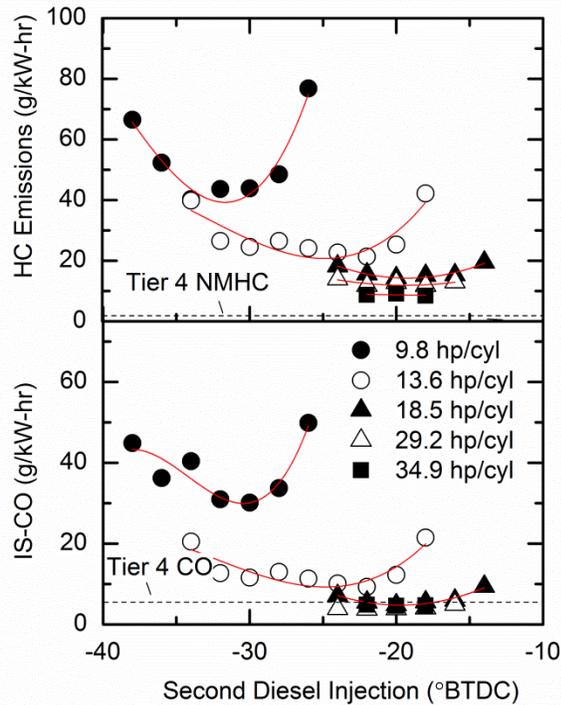
Engine indicated thermal efficiency is defined as the indicated power divided by the energy flow of fuel coming into the engine. Figure 5 shows indicated efficiency for tested engine load conditions. It remained high over the diesel injection timing range but decreased slightly at early second diesel injection timing. The chart illustrates that a peak in efficiency was found for each load as a function of diesel timing. As the engine load increased the optimal timing location for peak efficiency moved later toward top dead center (TDC) and the peak efficiency increased with increasing load. Near 50% indicated efficiency compared with the efficiency obtained with conventional diesel combustion with no ethanol added. Overall, no thermal efficiency advantage was found for RCCI over conventional diesel-only operation. This is primarily due to higher thermodynamic cycle efficiency being offset by poorer combustion efficiency. Combustion efficiency is a measure of the portion of incoming fuel that remains unburned and has a direct effect on overall thermal efficiency.
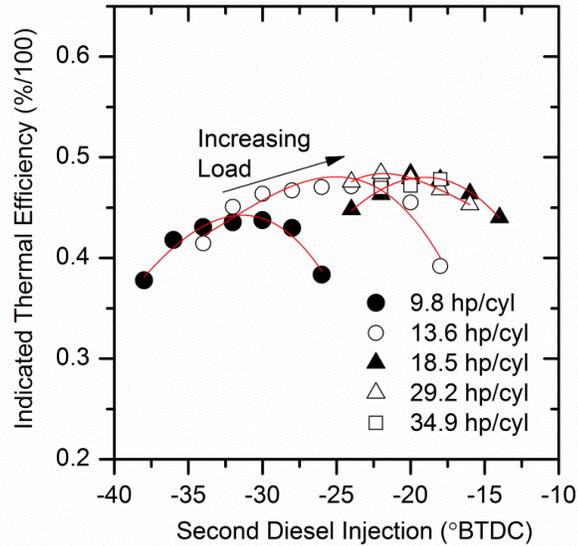
Figure 5: Engine indicated efficiency as a function of 2nd diesel injection timing in the RCCI mode. Engine operating conditions: 150 proof ethanol, engine speed = 1500 rpm, ethanol energy fraction = 75%.

Following the parameter sweep experiments, Response Surface Method (RSM) was applied to optimize the RCCI operating parameters for engine performance and emissions improvement and characterize the effect of different operating parameters on RCCI combustion. The goal of the RSM analysis was to find the optimum engine settings for dual fuel hydrous ethanol RCCI. RSM is a set of mathematical and statistical techniques seeking to optimize an objective function (or response) that is affected by multiple factors using design of experiments (DoE) methods and statistical analysis The RSM experiments were completed at two engine loads, 10 and 22 hp/cylinder, using 150 proof hydrous ethanol. In this study, the response variable was defined as in Equation 1, describing the objectives as to obtain an overall minimum of weighted CO_2, HC, CO, NO_X and soot emissions.

$$f(X) = \textbf{RESPONSE} = \frac{1000}{\left(\frac{IS-CO_2}{IS-CO_{2t}}\right)^2 + \left(\frac{IS-HC_t}{IS-HC_t}\right)^2 + \left(\frac{IS-CO}{IS-CO_t}\right)^2 + \left(\frac{IS-NOx}{IS-NOx_t}\right)^2 + \frac{IS-Soot}{IS-Soot_t}} \quad \text{Equation 1}$$

In the equation: X={x_1, x_2... x_n} denotes the vector of operating parameters to be optimized; IS-CO_2, IS-HC, IS-CO, IS-NO_X and IS-Soot denote measured emissions on an indicated specific basis; IS-CO_{2t}, IS-HC_t, IS-CO_t, IS-NO_{Xt} and IS-$Soot_t$ denote target values for the indicated specific emissions.

Settings of operating parameters obtained from previous RCCI evaluation testing were used for the starting points of the RSM experiments, and Table 3 lists selected settings.

Table 3: Two engine conditions chosen for optimization

Engine Load (hp/cylinder)	10	22
Engine Speed (rev/min)	1500	1500
Diesel SOIC 1 (ºATDC)	-60	-60
Diesel SOIC 2 (ºATDC)	-32	-22
DI Injection Pressure (bar)	400	800
Fraction of 1st Diesel Injection (%)	60	60
Ethanol Energy Fraction (%)	75	75
Intake Temperature (ºC)	102	43
Intake Pressure (bar)	1.6	1.9
EGR rate (% vol.)	0	29
Fuel/Air Equivalence Ratio	0.31	0.60

The process of the RSM experiments is described as following.

1. A set of factor screening experiments was conducted for each load condition. The 8 operating parameters that were selected as the candidates were: dwell between the 1st and 2nd diesel injection (dwell), 2nd diesel injection timing (SOI2), fraction of the 1st diesel injection (Inj1Fr), diesel rail pressure (RailP), fumigant energy fraction (FEF), EGR rate (EGR), intake air temperature (IntT), and intake air pressure (IntP), and they are listed in Table 4. A two-level fractional factorial design with resolution IV was used for these experiments. It was found that 5 operating parameters out of the initial 8 were significant for the low load condition which were SOI2, Inj1Fr, RailP, FEF and IntP. For the high load condition, the active factors were Dwell, Inj1Fr, RailP, IntT and EGR.

Table 4: Engine Parameters of Interest for Optimization

Symbol	T_{int}	P_{int}	EGR	Dwell	SOIC2	P_{rail}	Inj1Fr	FEF
Operating Parameter	Intake Temperature	Intake Pressure	EGR Rate	Interval between Two Injections	Second Diesel Injection Timing	Diesel Fuel Rail Pressure	Fraction of First Diesel Injection	Fumigant Energy Fraction

2. A set of experiments was conducted subsequently with respect to the active operating parameters to find the optimization path for the response at each load. The experimental design was a two-level fractional factorial design with resolution V and repeated center points. A first-order model was then fit to the experimental results, and it was found that the lack of fit (LoF) of the model was significant for both loads, indicating that the first-order model is not sufficient to describe the system.
3. The experimental design in Step 2 was then augmented with axial points to build a second-order model. Through ridge analysis for the second-order model, an optimization path for the response was obtained for each load.
4. Experiments were conducted along the optimization paths obtained in Step 3. A maximum value of response was obtained before encountering physical limits of certain operating parameters. For the high load condition, the predicted optimal intake air temperature and fraction of diesel fuel based on the ridge analysis were too low for stable combustion to maintain. Accordingly, these two parameters were raised up with respect to their predicted values for stable operation in the steepest ascent experiments. A comparison of selected performance and emissions results between the optimal points, the starting points and the

target values is given in Table 5. At the low load condition, the primary improvement was that the NO_X emissions were remarkably reduced from 2 g/kW-hr to 0.31 g/kW-hr, below the Tier 4 limit which is 0.4 g/kW-hr. However, the thermal efficiency and HC and CO emissions were compromised. At high load, NO_X, HC and CO emissions were substantially reduced as a result of the optimization, while a slight decrease in thermal efficiency was observed despite an improvement of combustion efficiency.

Table 5: Comparison of starting points and optimal points results at 10 and 22 hp/cylinder loads

	Indicated Efficiency	Comb. Efficiency	IS-CO$_2$	IS-NOx	IS-soot	IS-HC	IS-CO
	-	-	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr
10 hp/cyl Target	-	-	536.8	0.32	0.0080	17.34	11.70
10 hp/cyl Start	0.451	0.894	455.4	1.988	0.0060	21.6	23.1
10 hp/cyl Optimal	0.438	0.888	492.0	0.312	0.0028	27.0	16.9
22 hp/cyl Target	-	-	536.8	0.32	0.0080	17.34	11.70
22 hp/cyl Start	0.467	0.926	518.7	0.558	0.0008	19.0	7.5
22 hp/cyl Optimal	0.456	0.962	546.1	0.155	0.0010	9.5	4.6

Based on our findings, we have determined that RCCI with hydrous ethanol is feasible over nearly the entire load range of the engine. Emissions of NO_X and soot are reduced to below EPA off-road Tier 4 levels and engine fuel consumption stayed constant.

A multi-cylinder test of the dual-fuel RCCI system was not performed as part of this project as the single-cylinder experiments were found to be sufficient to prove the hypothesis that hydrous ethanol could be used to reduce emissions in diesel engines. However, future work is considering multi-cylinder dual-fuel diesel engines operating on hydrous ethanol, fulfilling this objective.

Results of Technology or Process Assessed:

Through this project, we found that using hydrous ethanol in a dual-fuel configuration could reduce emissions of diesel engines to regulated levels without aftertreatment and maintain efficiency compared to diesel only operation. It also showed that complete control over the engine is required to obtain these benefits. In practice, the solution developed here would need to be implemented by and engine original equipment manufacturer (OEM). We have communicated the results of our study at technical conferences and to engine OEMS directly. Based on these discussions, we have concluded that for dual fuel engine technology to succeed, a significant market needs to be developed for hydrous ethanol before an OEM solution can be viable. We believe that there is considerable incentive to reduce emissions using dual fuel hydrous ethanol/diesel especially in the off-highway engine market where strict regulatory standards are requiring expensive aftertreatment systems. Identified markets for a dual-fuel system include stationary generators, irrigators, tractors, locomotive and shipboard engines.

Benefit to Minnesota Economic Development:

Expanding the market for fuel ethanol could have a significant impact on Minnesota's economy. This project has shown that hydrous ethanol can replace a significant amount of diesel fuel use in Minnesota if dual-fuel engines were commercially available. An additional market for fuel ethanol could help growers and producers by allowing them to reduce risk and potentially expand their operations. Despite the potential of hydrous ethanol, dual fuel engines will not be produced by engine OEM's unless fuel infrastructure is installed and a clear market demand from consumers is proven.

Marketing:

Results from this project have been published at several conferences and in peer-reviewed technical journals[5,6,7]. The PI Northrop has also discussed results from the project with OEM engine manufacturers including Cummins and John Deere. Highlights from this project have also been publicized in Ag Innovation News, the University of Minnesota's Center for Transportation Studies Catalyst newsletter.

Conclusions:

The aim of this research is to demonstrate high efficiency, low emissions engine operation in a modified diesel engine with hydrous ethanol providing up to 80% of the fuel energy input. A new dual-fuel combustion concept, reactivity controlled compression ignition (RCCI) has been used to reduce soot and oxides of nitrogen (NO_X) emissions while maintaining very high engine efficiency. RCCI operation has been successfully demonstrated over a wide range of engine load. NO_X and soot emissions well below the US EPA Tier 4 standards have been achieved, at the expense of slightly lower thermal efficiency and higher HC and CO emissions than in conventional diesel engines. With such remarkable improvement in engine-out NO_X and soot emissions, the demand for catalytic aftertreatment can be significantly reduced. A Design of Experiments technique, Response Surface Method, has been applied to optimize the RCCI operating parameters at different load conditions, and significant improvement on the overall engine performance and emissions has been gained.

This work has successfully shown that significant emissions reductions can be obtained using hydrous ethanol in a diesel engine with complete control of the engine fuel injection calibration. Such results could impact diesel engine manufacturers to consider the use of hydrous ethanol dual-fueling as a viable option for future products.

Future Needs/Plans:

Based on the successful technical results of this project, future work should be directed towards developing a market for, and source of hydrous ethanol. These two tasks are being addressed through current projects funded by the MN Corn Growers and AURI. In the first, "Development of a Port-Injected Hydrous Ethanol System for Diesel Engines" (AIC209), our goal is to develop an aftermarket hydrous ethanol injection system that can be easily installed on some diesel engines and that can achieve up to 50% FEF with 150 proof ethanol of without modifying the original electronic control unit of the engine. This aftermarket system will provide a way to commercialize dual-fuel diesel engines without an OEM solution, potentially leading the way to a larger market for diesel replacement with ethanol. As an extension of this work, we are hoping to demonstrate a hydrous ethanol dual-fuel engine in the field in the summer of 2015.

The second program related to this project is entitled "Quantifying Energy Savings Gained through Production of Hydrous Ethanol from Corn". The objectives of this project are to conduct a detailed analysis of

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[5] Northrop, W. F., Fang, W. & Huang, B. Combustion Phasing Effect on Cycle Efficiency of a Diesel Engine Using Advanced Gasoline Fumigation. in Proc. ASME 2012 Intern. Combust. Engine Div. Spring Tech. Conf. 1–8 (2012).

[6] Fang, W., Huang, B., Kittelson, D. B. & Northrop, W. F. Dual-Fuel Diesel Engine Combustion with Hydrogen, Gasoline, and Ethanol as Fumigants: Effect of Diesel Injection Timing. in *Proc. ASME 2012 Intern. Combust. Engine Div. Fall Tech. Conf.* 1–9 (2012).

[7] Fang, W., Kittelson, D. B. & Northrop, W. F. An Experimental Investigation of Reactivity-Controlled Compression Ignition Combustion in a Single-Cylinder Diesel Engine Using Hydrous Ethanol. in *Proc. ASME 2013 Intern. Combust. Engine Div. Fall Tech. Conf.* 1–9 (2013).

how hydrous ethanol of different proof could be efficiently produced at existing ethanol plants and determine the cost and energy savings that might result compared to anhydrous ethanol production. The project will lead the way to providing additional incentive for producers to provide hydrous ethanol to the marketplace.