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Improving alternative fuel efficiency with water injection

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Abstract

Alternative fuel internal combustion engines (ICEs) have been increasing in popularity as the harmful effects of pollution and the need for a sustainable energy source are becoming more apparent. Two alternative fuels, E85 and hydrogen gas, are considered in this study. These fuels are renewable and have less emissions than traditional fuels, but there are many inherent disadvantages to their use. Water injection could alleviate some of the issues that plague these fuels. To test this, a Briggs and Stratton Baja engine was used, with and without water injection. Gasoline with water injection showed better performance than without: the power with water injection was 10.26 hp while the power without injection was 10.35 hp. Further tests with E85 were planned, but due to equipment malfunctions, these tests could not be performed. Instead of experimental test results, theoretical curves for E85 were found. E85 had a performance that was 80% of gasoline's. Adding water injection increased E85's performance to 92% of gasoline's performance. These results show that water injection is capable of increasing engine performance. It is possible that the benefits of water injection could also apply to hydrogen fuel. Implementation of water injection in a hydrogen fuel ICE would alleviate some of the issues that are inherent in these systems, allowing for improvements in design and operation. Water injection could increase the viability of alternative fuel ICEs.

Contents

Introduction

Alternative fuels in internal combustion engines (ICEs) have seen a resurgence of interest and popularity in recent years. This is due in part to a desire to utilize sustainable fuels that are better for the environment. Alternative fuels have the potential to reduce greenhouse gas emissions, which is increasingly necessary. Emissions such as carbon dioxide (CO_2), methane (CH_4), and nitrogen oxides (NO_x) contribute to climate change. According to the EPA, transportation accounted for 27% of the total emissions in 2015, equaling 1.8 billion metric tons [1]. In addition to negative impacts on the environment, passenger vehicle emissions can also cause serious health concerns. The EPA estimated that cars and trucks account for half of all cancers caused by air pollution. In addition to cancer, respiratory issues such as pneumonia and asthma are exacerbated by these pollutants [2]. Through improved engineering, these pollutants could be decreased.

Alternative fuels are attractive with regards to emissions and sustainability when compared with gasoline and diesel, but they also have serious issues. Fuels such as hydrogen and ethanol suffer from lower power outputs when compared to gasoline under similar conditions [3,4,5,6]. The theoretical power output of a hydrogen engine is 15% lower than a comparable gasoline engine [5], while the fuel economy of ethanol can be up to a 25% reduction from gasoline [6]. Abnormal combustion effects such as backfire, engine knock, and autoignition plague alternative fuel ICEs [5].

Water injection could be a possible solution. Water injection can effectively increase the octane number of the fuel, which has the potential to improve engine performance and efficiency through higher compression ratios and reduced combustion temperatures [8]. Water injection also is a thermal dilution technique, which helps to prevent abnormal combustion effects [7].

Goal

The goal of this project is to expand upon current alternative fuel research. Water injection will be the focus of this study, where the viability of water injected alternative fuel ICEs will be evaluated. In this analysis, two alternative fuel types will be discussed: hydrogen gas and E85.

Additional Considerations

For the most part, this paper will avoid the topics of infrastructure, life-cycle costs, and life-cycle emissions. If the technology of alternative fuels was improved, then changing the infrastructure and reducing life-cycle costs is likely to happen as a result.

Literature Review

In a study entitled "Stoichiometric H_2ICE with Water Injection and Exhaust and Coolant Heat Recovery through Organic Rankine Cycles" by Alberto Boretti, Hydrogen fuel was tested with water injection. He concluded that by using port water injection and direction hydrogen injection, stoichiometric operation is possible due to the thermal dilution caused by the water injection. His study found that water injection and organic Rankine cycles could increase the power output of hydrogen ICEs, improving the efficiency by as much as 5.3% [8]. This improvement shows that water injection can have positive effects on hydrogen ICEs.

"An Experimental Study on the Effects of Bioethanol - Gasoline Blends on Engine Performance in a Spark Ignition Engine" by Aydogan and Ozcelic concludes that power decreased by approximately 20% from the use of ethanol blends and the specific fuel consumption increased by 15% [9]. These disadvantages of ethanol blends are important to note when considering ethanol in ICEs.

Busuttil, Camilleri, and Farrugia wrote a study called "Mechatronics for Water Injection in an SI Engine." From their experiments, they concluded that water injection can provide an increase in engine torque of up to 16% [10]. An improvement of this magnitude is significant and will be evaluated further in the results section.

In these studies, water injection effects with standard and alternative fuels and the results of using ethanol blends were discussed. These studies suggest that water injection can provide a much-needed improvement in alternative fuel ICE performance, forming a basis for moving forward on this project.

Hydrogen Internal Combustion Engines

Hydrogen has attractive properties when considered as an alternative fuel. It is a renewable resource and can have carbon-neutral emissions. Hydrogen fuel has a wide range of flammability, which means that the fuel can be burned extremely lean, up to an air-to-fuel ratio of 180 [5]. Lean fuels often have more complete combustion and get better fuel economy than stoichiometric or fuel rich mixtures. Hydrogen also has a higher flame speed than traditional fuels at stoichiometric ratios, allowing stoichiometric hydrogen ICEs to more closely approach ideal engine cycles. High diffusivity will allow hydrogen to mix faster with air than other fuels, producing a more homogeneous substance in the combustion chamber. The autoignition temperature of hydrogen gas is higher than gasoline, allowing larger compression ratios to be used in hydrogen ICEs, which improve engine efficiency and power output [2].

Hydrogen fuel has several major drawbacks. One of the most infamous properties of hydrogen fuel is its tendency to explode. This is mainly due to its low ignition energy. In ICEs, hot spots are formed inside the engine's combustion chamber. These hot spots can often be enough to cause hydrogen to pre-ignite. Preignition can cause engine knock, amongst other issues, potentially damaging the engine. In addition to preignition issues, hydrogen fuel has a low energy density. This low energy density means that more hydrogen than gas needs to be burned to achieve comparable power outputs. Hydrogen gas also burns at higher temperatures than gasoline, causing an increase in NO_x emissions when compared to standard fuels [2].

Extensive research and development into hydrogen ICEs has occurred in recent years. Several large auto companies have created hydrogen concept vehicles. BMW created the Hydrogen 7 in 2005. This vehicle had a top speed of 140 mi/h and a maximum power of 256 hp at 4300 rpm. The capabilities of this car are impressive, but it required 12 cylinders to achieve this output, which reduces the practicality of the vehicle. Mazda also developed a hydrogen vehicle. The Mazda RX-8 Hydrogen RE used a rotary engine to prevent backfire. While running on hydrogen, the engine had an output of 109 hp at 7200 rpm. Ford introduced a fleet of shuttle buses, called the E-450, that ran on hydrogen fuel. These ICEs produced 235 hp at 4000 rpm [13]. To accomplish this, the buses had 6 hydrogen tanks and solenoid valves. Even with all these developments, hydrogen ICEs are currently not viable.

E85 Internal Combustion Engines

E85, often called flex fuel, has been regularly used by consumer vehicles for several years. The increasing usage of E85 is due to the benefits that this fuel has, like being a renewable resource. Ethanol can be produced from any biomass that can be converted into sugars, such as corn. Because of the wide range of production sources, ethanol can be produced domestically, removing transportation costs from the fuel price and allowing for cheaper fuel. E85 also has a high octane number of up to 108.6, which will allow for increased engine performance and a longer engine life [9].

Ethanol has several downfalls. The fuel has a lower energy content than gasoline, causing a decrease in engine power. Pure ethanol has 76,330 Btu of energy, while gasoline has anywhere from 112,000 to 116,000 Btu. Because of the low energy content, fuel economy will be lower than that of gasoline by as much as 25% [6]. A decrease in energy will cause a power decrease from use. One study showed that the torque and power can decrease by up to 20%, depending on the percent ethanol content in the blend [9]. Ethanol is a hydrocarbon, which means that it will still produce CO_2 when combusted, limiting its appeal as an alternative fuel. The use of ethanol also has a societal impact. By using crops such as corn in fuel production, the cost of food can increase from an increased demand of ethanol fuels.

Water Injection

Water injection has many proven benefits in improving the engine performance of gasoline and diesel engines. The introduction of water into the engine can cool the combustion chamber. If the combustion chamber is too hot, hot spots will form, which can have a negative impact on engine life as well as lead to preignition. Preignition is a frequent problem for alternative fuels such as hydrogen [8].

A cooler combustion chamber allows for higher compression ratios. Compression ratio is defined as

$$r = \frac{v_{BDC}}{v_{TDC}} \qquad (1)$$

where *r* is the compression ratio, *v* is volume, and *BDC* and *TDC* represent bottom dead center and top dead center, respectively. Compression ratios are limited by the fuel's autoignition temperature, or the point at which it will combust from a pressure increase. Equation 2 shows a relationship between temperatures and the compression ratio by

$$\frac{T_{TDC}}{T_{BDC}} = (r)^{k-1} \qquad (2)$$

where *T* represents temperature and *k* is the ratio of specific heats. From Equation 2, if T_{BDC} is constant, an increase in *r* will cause an increase in T_{TDC}. Autoignition can occur if the temperature at top dead center is higher than the autoignition point of the fuel being used. By using a fuel with a higher autoignition temperature, a higher compression ratio can be used.

The benefit of this increased compression ratio is improved engine performance. Thermal efficiency, shown in Equation 3, will increase as the compression ratio increases [11]. It is important to note that the Otto cycle is an idealized case with an isentropic assumption. The equation is used here to represent a relationship between compression ratio and efficiency, but it is not used to calculate these efficiencies.

$$\eta_{th,Otto} = 1 - \frac{1}{r^{k-1}} \qquad (3)$$

In this formula, $\eta_{th,Otto}$ is the thermal efficiency.

An additional benefit of the cooling of the combustion chamber is the temperature reduction of engine exhaust. Since NO_x production is a function of temperature, the lower exhaust temperature will reduce the amount of NO_x produced [8]. This property of water injection is important, as NO_x emissions are a key environmental concern.

Experimental Setup

A Briggs and Stratton Model 19 SAE Baja Engine was used in testing. This engine, shown in *Figure 1*, has the following characteristics.

Table 1*: Model 19 Baja Engine Specifications*

SPECIFICATIONS		
MODEL/TYPE(S) 19L232-0054 G1	**DISPLACEMENT** 305	**BORE/STROKE** 3.12" / 2.44"
COMPRESSION RATIO 8.1 to 1	**FACTORY TIMING** 23 degress BTDC	**HP (GROSS)*** 10.0 hp
OIL CAPACITY (DRY) 24 ounces	**FACTORY SET RPM** 3,800 RPM	**FUEL TYPE** 87 Octane

Figure 1*: Model 19 Baja Engine*

The Model 19 has the following manufacturer specified performance curves which show net power and net torque vs. engine speed.

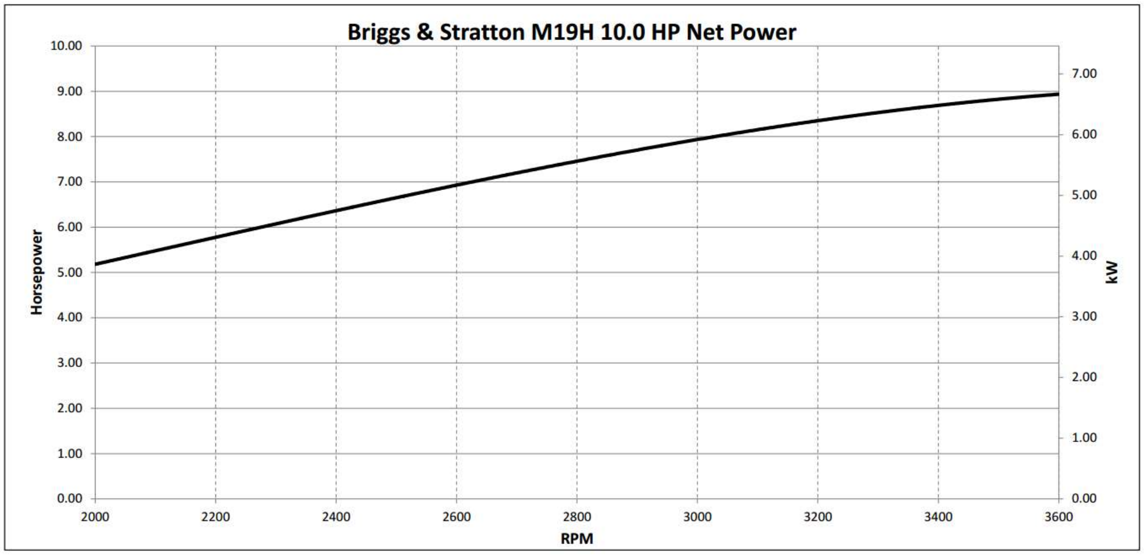

Figure 2*: Model 19 Net Power*

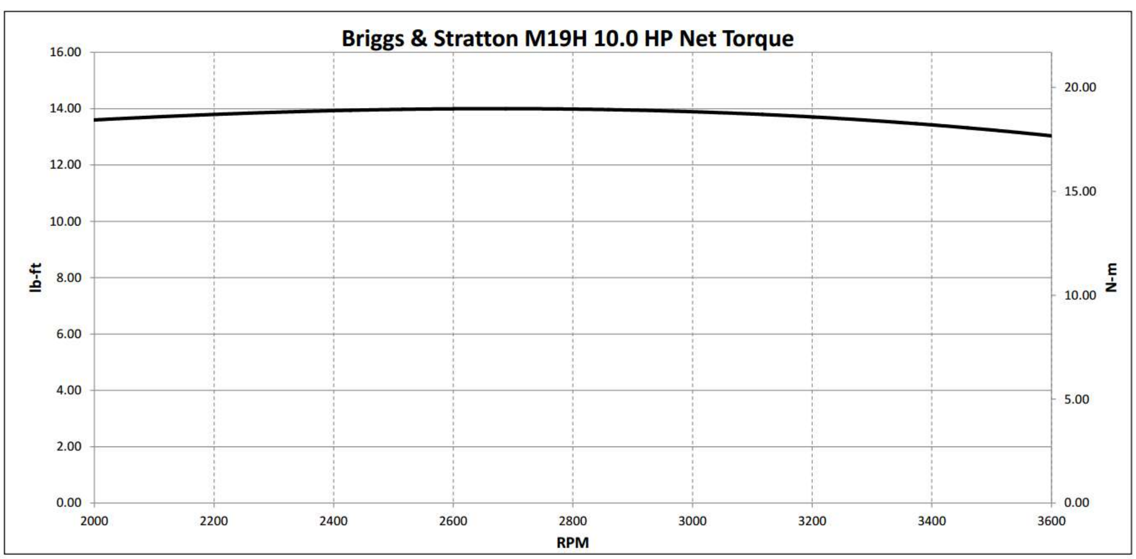

Figure 3*: Model 19 Net Torque*

The engine shaft was attached by belt to a Land & Sea dynamometer. This dynamometer read rpm, horsepower, torque, and engine temperature. A hydrodynamic load was used to regulate the dynamometer. The water source was a pump that produced 70 psi. Output from the dynamometer was read by the software package Dyno-Max. A user interface of this program is shown in the Appendix.

Figure 4*: Land & Sea Dynamometer*

To test water injection, An AEM injection kit, *Figure 5*, was used. This kit was designed for a 6-cylinder engine, so it had to be scaled down to provide an appropriate water flow rate, which was accomplished with a smaller nozzle than came in the kit. Using a water-to-fuel mass ratio of 0.75 [12], calculations were run to find the proper amount of water that needed to be introduced. Water flow rate calculations are shown in the Appendix, where a flow rate of 0.5 gallons per hour was found.

***Figure 5**: AEM Water Injection Kit*

Methodology

To test for changes in net power and torque, a throttle sweep test was performed. This involved starting the engine and using the throttle to gradually increase the rpm. The Land & Sea dynamometer was fully loaded at 70 psi during the entirety of testing, which was done to allow consistent results. Five trials were run for gasoline and gasoline with water injection. Each trial had a total of five sweeps, producing twenty-five sweeps for each engine condition.

Results

Gasoline

Figure 6 shows the testing results for gasoline. An average line, as indicated by the figure's legend, is plotted. This line represents average power values at each rpm.

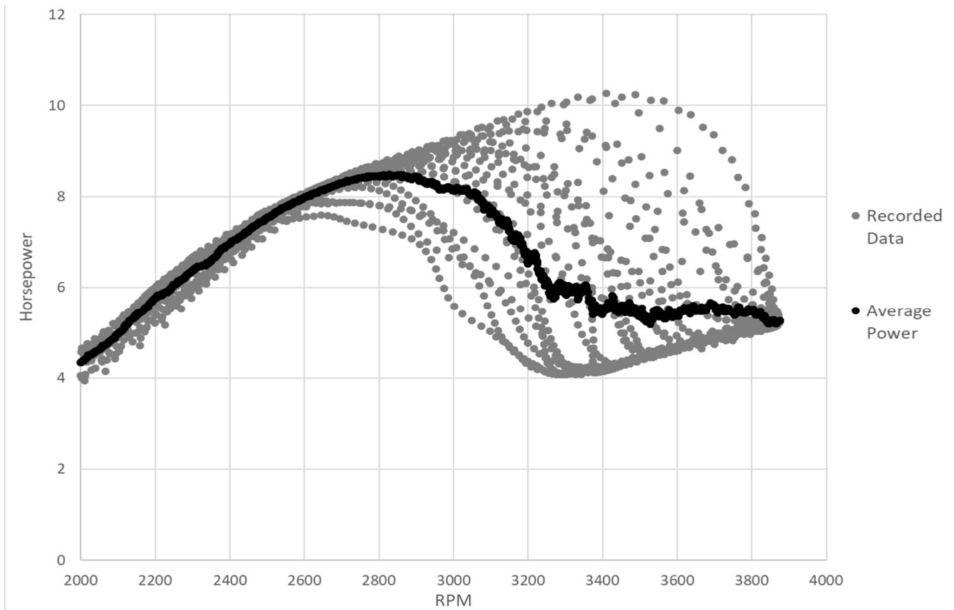

***Figure 6**: Net Power, Gasoline*

The maximum recorded horsepower for gasoline was 10.26 hp at 3409 rpm. This power is higher than the rated horsepower of the engine by 2.6%.

In *Figure 7*, net torque is plotted.

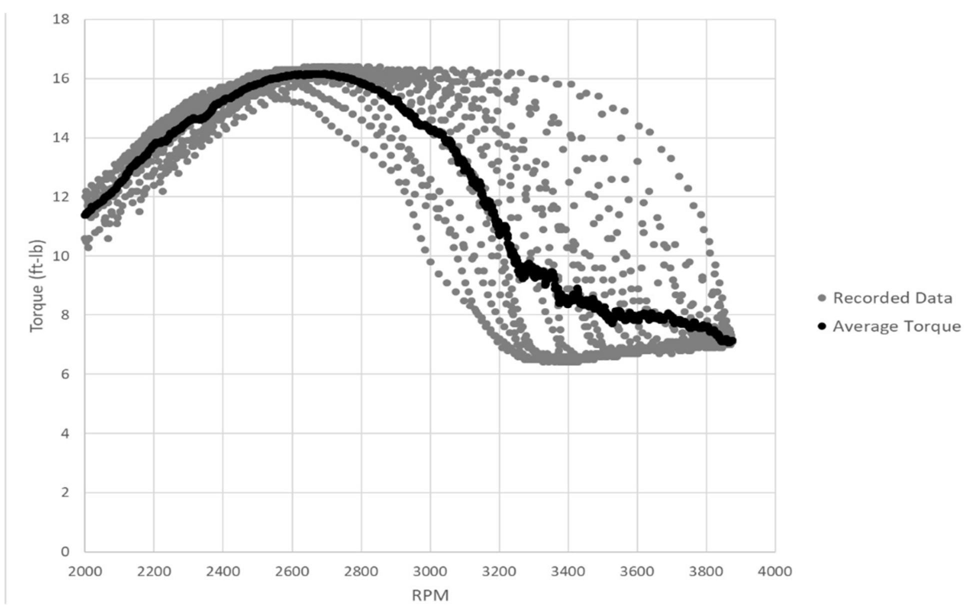

***Figure** 7: Net Torque, Gasoline*

The maximum recorded torque was 16.4 ft-lb at 2854 rpm. The torque value is higher than the engine specified maximum by 17%.

Gasoline with Water Injection

After running tests with gasoline, water injection was tested. The net power results for gasoline with water injection can be seen in *Figure 8*. Likewise, the net torque results can be seen in *Figure 9*.

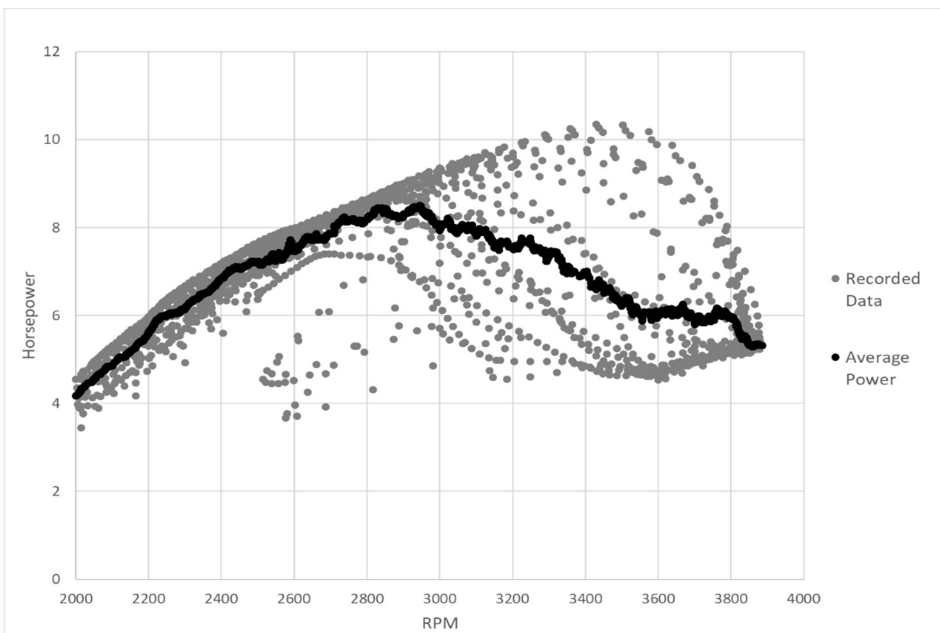

Figure 8*: Net Power, Gasoline with Water Injection*

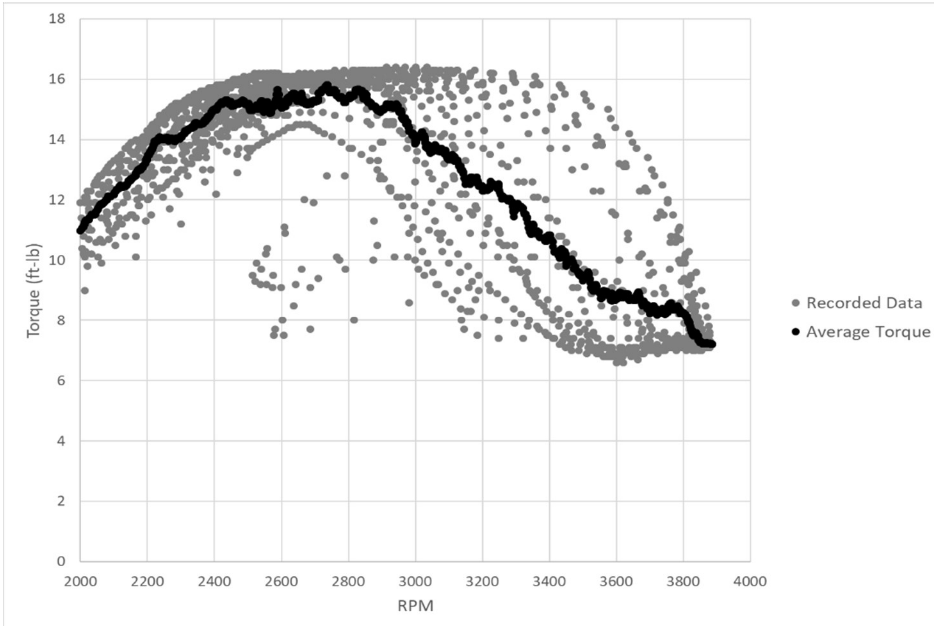

Figure 9*: Net Torque, Gasoline with Water Injection*

As can be seen from these plots, the maximum horsepower rating is 10.35 hp at 3409 rpm and the maximum torque rating is 16.4 ft-lb at 3034 rpm. These values are 3.5% and 17% above the manufacturer specified values, respectively.

Ethanol Calculations

Experimental tests with ethanol were not able to be performed due to equipment malfunctions. Instead of experimental data, theoretical calculations based on the gasoline results were performed. E85 has approximately a 20% lower performance than gasoline. Using this percentage, calculations were made to find curves, which can be found in *Figures 10* and *11*.

Ethanol Calculations with Water Injection

The theoretical values produced for E85 were used to find values for E85 with water injection. A theoretical performance increase of 15% was used. The results of this calculation can be seen in *Figures 10* and *11*.

Comparisons

In *Table 2*, maximum horsepower and torque for each condition are shown.

Table 2*: Maximum Power and Torque Comparison*

	Horsepower	RPM	Torque (ft-lb)	RPM
Gasoline	10.26	3409	16.4	2854
Gasoline with water injection	10.35	3430	16.4	3034
E85	6.79	2828	12.94	2695
E85 with Water Injection	7.81	2828	14.88	2695
Manufacturer Specifications	10	3800	14	2600

All the average power and torque lines for the different engine conditions have been compiled in *Figures 10* and *11*.

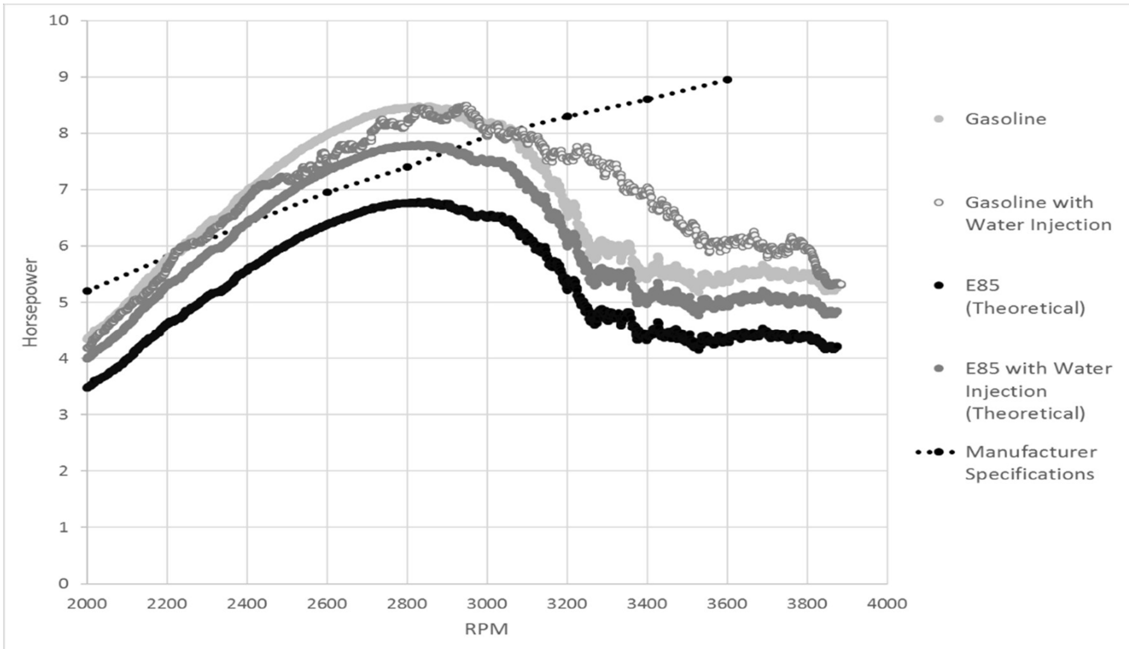

Figure 10: *Net Power of All Conditions*

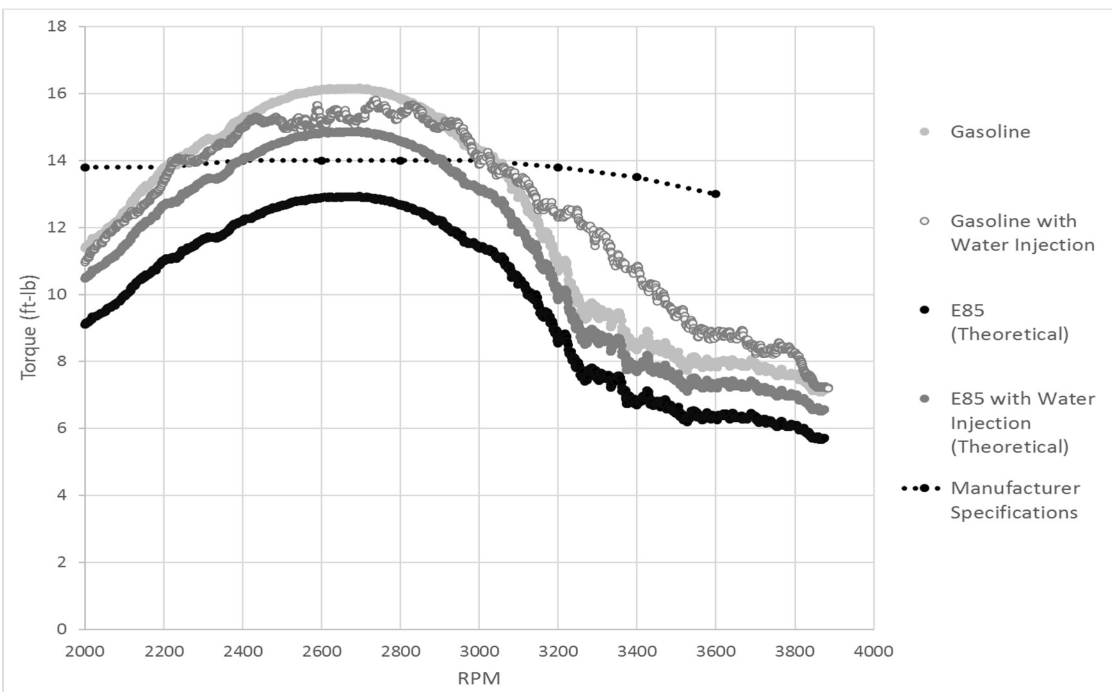

Figure 11: *Net Torque of All Conditions*

Discussion of Results

When comparing experimental results to the manufacturer's specifications, the two are markedly different. There are several factors that could contribute to this. The engine that was used is several years old and has been used in SAE Baja competitions, causing many hours of operation. It is likely that this engine has accumulated wear that could change the way that it performs at higher rpms. The engine was also run without an air filter to simplify the apparatus setup. This could affect how much air and fuel is drawn into the combustion chamber. Another factor could be miscalibration of the dynamometer. The rpm was independently verified with a handheld tachometer and the torque arm was calibrated by a dead-weight test, but software or unforeseen issues with the dynamometer could affect the results. The engine was tested under full load, which could be another contributing factor. A full load was used in testing for consistency in loading, but it could have put more stress on the engine, causing the power to peak at a lower rpm.

It is also worth noting that significant variations in the performance curves can be obtained from different trials of the same test. This is likely due to throttle ramping. The rate at which the throttle was applied determines how quickly the performance will decrease after peaking, which is evident in the produced performance curves. By pulling the throttle at different rates, different performance curves could be produced.

As was expected, gasoline with water injection had the highest power output and torque at 10.35 hp and 16.4 ft-lb, respectively. As can be seen in *Table 2*, gasoline had the next highest performance. E85 with water injection has a performance curve that is 8% lower than gasoline without water injection. E85 without water injection has a lower performance curve at 20% of that of gasoline. From this testing, it has been shown that water injection can improve ICE horsepower and torque. Water Injection performed best above 3000 rpm. This is likely because there was too much water injected for the lower rpm. Once the rpm increased, the water mass flow was at an optimal value, which allowed water to improve gasoline results.

Conclusions

The main goal of this study was to compare the results of E85 with water injection to gasoline. Looking at *Figure 10* and *11*, E85 with water injection performs at about 92% of gasoline's output as compared to E85 without water injection's 80%. With a difference of only 8% from regular gasoline to E85 with water injection, these two fuel systems could be considered comparable. With ethanol's lower price and high octane number, ethanol is shown to be an attractive alternative fuel when it is coupled with water injection.

Showing how water injection can improve performance can be extrapolated to other fuels. Water injection would have similar benefits for hydrogen fuel. In addition to improving performance, water injection will mitigate several of the issues with hydrogen, such as preignition. Water injection could also allow for high compression ratios in hydrogen ICEs. As shown in Equation 3, a high compression ratio means a higher thermal efficiency. The hypothesized increase in thermal efficiency from water injection could contribute to hydrogen being a more viable fuel source in ICEs.

Through the improvement of alternative fuels efficiency, water injection could positively contribute to the environment. The use of sustainable fuels and a reduction in emissions will lead to a cleaner planet and improved health for all.

Recommendations

The next step of this research is to test E85. Equipment issues prevented testing this fuel, but experimental results would allow this research document to be more complete.

One way to improve the project results would be to use a larger engine. Using a small, single-cylinder engine is difficult because the output changes are nominally small. For example, A 5% change in output could be 0.1 horsepower, which because of the small magnitude could be caused by external disturbances and not water injection.

An improved water injection system should be implemented. Controlling water injection accurately and precisely is necessary to get reliable results.

An apparatus that could test for emissions would provide useful data. NO_x emissions will differ between the fuel types, so it would be interesting to see how they differ.

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Appendix

Water Flow Calculations

WF ratio found in Effects of Water Injection and Increased Compression Ratio in a Gasoline Spark Ignition Engine

AF=	9.8
WF ratio=	0.75
r=	8.1

Vd=	305	cm^3	
Vd=	0.000305	m^3	
density=	1.184	kg/m^3	(25C, 1atm)

RPM	Draw strokes	m_air (kg/min)	m_fuel (kg/min)	m_water (kg/min)
1000	500	0.18056	0.01842449	0.013818367
1500	750	0.27084	0.027636735	0.020727551
2000	1000	0.36112	0.03684898	0.027636735
2500	1250	0.4514	0.046061224	0.034545918
3000	1500	0.54168	0.055273469	0.041455102
3500	1750	0.63196	0.064485714	0.048364286
4000	2000	0.72224	0.073697959	0.055273469

		m_water						
RPM	Draw strokes	kg/min	kg/hr	lb/min	gal/min	gal/hr	mL/min	mL/hr
1000	500	0.013818367	0.829102041	0.030463973	0.00365714	0.219428374	13.84377272	830.6263629
1500	750	0.020727551	1.243653061	0.045695959	0.005485709	0.329142562	20.76565907	1245.939544
2000	1000	0.027636735	1.658204082	0.060927945	0.007314279	0.438856749	27.68754543	1661.252726
2500	1250	0.034545918	2.072755102	0.076159932	0.009142849	0.548570936	34.60943179	2076.565907
3000	1500	0.041455102	2.487306122	0.091391918	0.010971419	0.658285123	41.53131815	2491.879089
3500	1750	0.048364286	2.901857143	0.106623904	0.012799989	0.767999311	48.4532045	2907.19227
4000	2000	0.055273469	3.316408163	0.121855891	0.014628558	0.877713498	55.37509086	3322.505452

Dyno-Max User Interface