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Article

A comparison of small engine emissions powered by alcohol and gasoline fuel

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SUMMARY
Small engines create a disproportionate amount of pollutants for their size. No research on the emissions of a small, carbureted engine run on widely available 100% alcohol fuel exists. To address this problem, we hypothesized that an alcohol-based fuel could be used as an effective means of lowering small engine emissions. To investigate the extent of small engine emissions improvement, a Toro push lawn mower with a 6.5 hp engine was modified to run on alcohol fuel. We tested for the common pollutant's nitrous oxide, unburnt hydrocarbons, sulfur dioxide, and carbon monoxide using a Testo 350 portable emissions analyzer. Two fuels were used. The first was Klean Strip Denatured Alcohol, which is a mixture of ethanol and methanol. The second was made up of 10% ethanol and 90% gasoline (E10) and is available at most gas stations. The Klean Strip Denatured Alcohol fuel produced significantly less nitrous oxides, sulfur dioxide, carbon monoxide, and hydrocarbon emissions when compared to the E10 fuel. Of the four measured pollutants, the alcohol-based fuel consistently produced at least 40% less emissions compared to the E10 fuel. The use of a methanol and ethanol blend in small engines could drastically reduce existing small engine emissions.

INTRODUCTION
Small engine emissions are harmful for several reasons, one being that the operator is usually close to the exhaust. A previous study found that chainsaw operators were exposed to 400 parts per million (ppm) of carbon monoxide for 10-second periods (1). This repeated exposure is unhealthy and can cause many serious health problems, such as Parkinson's disease (2). Emissions such as nitrous oxide and sulfur dioxide can also contribute to acid rain, which reduces biomass (3). Excess unburnt hydrocarbons are also prevalent in small engine exhaust and are known to cause smog (4).

A promising solution to cut down on these pollutants is alcohol-gasoline blends. Eyidoğan et al. used alcohol-gasoline blends including 10% ethanol + 90% gasoline (E10), 5% ethanol + 95% gasoline, 10% methanol + 90% gasoline, and 5% methanol + 95% gasoline (5). They tested the effects of these alcohol-gasoline blends on small engine hydrocarbon emissions and found that these alcohol-gasoline blends increased efficiency, and decreased hydrocarbon emissions (5). Ethanol and methanol's high latent heat and high oxygen content led to more complete combustion and decreased hydrocarbon output (6, 7). The federal government of the United States mandated that alcohol be blended with gasoline in 2003 for similar reasons (8). These previous studies established a connection between alcohol blended with gasoline and increased efficiency and contributed to our hypothesis that fuel made up entirely of alcohol could be used as an effective means of lowering small engine emissions (4, 5). Although small engine emissions can also be reduced by re-engineering the engine design, this is very expensive and extremely impractical for existing small engines (6).

In this study, we aimed to test the emissions of a small engine with minimal modifications running on two fuels. The first is Klean Strip Denatured Alcohol, which is a mixture of 30-50% ethanol and 40-60% methanol (9). The second fuel, E10, is available at many gas stations and is made up of 10% ethanol and 90% gasoline. The emissions of the small engine running on 100% alcohol fuel were compared to the emissions of the same engine running on E10. Specifically, we report the effectiveness of 100% alcohol fuel compared to E10 from a standpoint of nitrous oxides, sulfur dioxide, hydrocarbon, and carbon monoxide emissions. We found that alcohol fuel reduced the amount of the previously stated pollutants by at least 40% when compared to gasoline. In the future, we would like to further investigate how different blends of alcohol and other alternative fuels impact the emissions of a small engine.

RESULTS
We theorized that by converting a typical gasoline-powered small engine to alcohol fuel, the emissions of carbon monoxide, nitrous oxides, hydrocarbons, and sulfur dioxide would decrease. We collected emissions data while the lawn mower was running on 100% alcohol fuel and separately while it was running on E10. A Testo 350 Engine Kit with an emissions measurement wand was inserted into the muffler of the lawn mower at the 1, 2.5, and 5-minute marks. The wand was inserted for 30 seconds, and emissions were measured every second for 30 seconds then an average was developed from the 30 measurements.

The carbon monoxide (CO) emissions of the lawn mower run on gasoline were 13,145.76, 20,917.58, and 28,005.66 ppm comparatively when run on alcohol they were 481.32, 452.44, and 542.72 ppm at 1, 2.5, and 5 minutes respectively (**Figure 1**). Alcohol fuel reduces carbon monoxide emissions by 25 times when compared to gasoline. The CO emissions of the engine run on gasoline follow a linear relationship. Compared to the CO emissions of the engine run on alcohol which drops at 2.5 minutes and then returns to a linear pattern. Overall, CO emissions from the lawn mower run on alcohol were significantly less than when run on gasoline ($p < 0.005$, two-sample t-test).

The nitrous oxide (NO) emissions when the lawn mower was run on gasoline were 50.72, 59.16, and 64.3 ppm and 20.68, 31.14, and 37 ppm when run on alcohol at 1, 2.5, and 5 minutes, respectively (**Figure 2**). At all time points, NO

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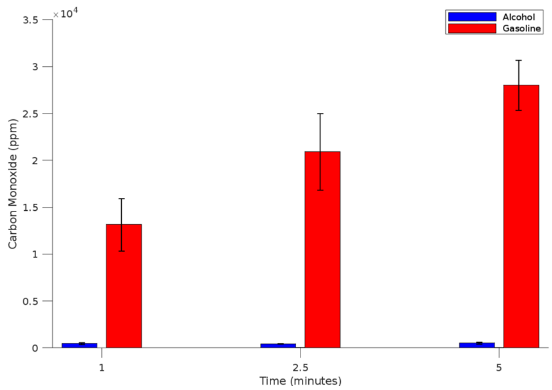

Figure 1: Comparison of carbon monoxide (CO) emissions. Difference in the CO emissions of two fuel sources, alcohol and E10 gasoline, when used as fuel for a small engine. Data is shown as mean ± SEM. Measurements of CO were taken by inserting a probe at the 1, 2.5, and 5-minute marks for 30 seconds. These measurements constituted 1 trial; 5 trials were conducted for each fuel. The results of a two-sample t-test were all less than 0.005.

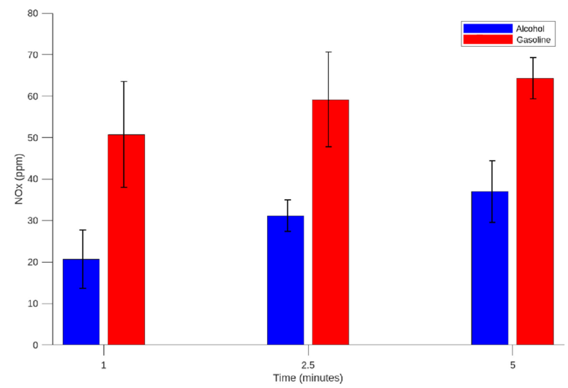

Figure 2: Comparison of nitrous oxide (NO) emissions. Difference in NO emissions of two fuel sources, alcohol and E10 gasoline, when used as fuel for a small engine. Data is shown as mean ± SEM. Measurements of NO were taken by inserting a probe at the 1, 2.5, and 5-minute marks for 30 seconds. These measurements constituted 1 trial; 5 trials were conducted for each fuel. The results of a two-sample t-test were all less than 0.005.

emission when run on alcohol were significantly less than when the lawn mower was run on gasoline ($p < 0.005$, two-sample t-test). The values of both sets of data given their respective times follow a more traditional curve of increasing emissions as time increases.

The hydrocarbon emissions of the lawn mower follow a similar trajectory. When the lawn mower was run on gasoline the hydrocarbon emissions were 10,679.8, 14,156.2, and 15,584.2 ppm comparatively when run on alcohol fuel they were 538.6, 898.4, and 1483.2 ppm at 1, 2.5, and 5 minutes, respectively (**Figure 3**). The data demonstrates that alcohol fuel more than halves the hydrocarbon emissions compared to gasoline ($p < 0.005$, two-sample t-test).

The average sulfur dioxide emissions of the lawn mower when run on gasoline were 356.2, 502.8, and 633.4 ppm vs. 27.8, 54.6, and 58.6 ppm when run on alcohol at 1, 2.5, and 5 minutes, respectively (**Figure 4**). The sulfur dioxide emissions of alcohol when compared to gasoline were at least 4 times less and significantly different ($p < 0.001$, two-sample t-test). Overall, we found that compared to E10 gasoline, 100% alcohol fuel produced less pollutants in all measured categories. This difference was significant with $p < 0.005$ for all two-sample t-tests performed.

DISCUSSION

The difference between alcohol and gasoline CO and hydrocarbon emissions exists largely because the two components of alcohol fuel—methanol and ethanol—contain oxygen, whereas the main components of gasoline do not (6). Gasoline's lack of oxygen results in incomplete combustion and increased production of harmful emissions (6). Ethanol's oxygen content is one reason why it is blended with gasoline in the United States (8). However, to fully utilize alcohol's combustion emission benefits as a fuel in small engines, our data shows that a 100% concentration of alcohol is more impactful.

Nitrous oxide emissions were lower when the engine ran on alcohol because both ethanol and methanol burn at lower temperatures than gasoline, leading to a less hospitable environment for nitrous oxides to form as they require high temperatures that gasoline combustion readily generates (10). Comparatively, a study of small engine NO emissions previously demonstrated a 77% reduction in NO between a blended fuel consisting of 9% ethanol 91% gasoline and pure gasoline (11).

Gasoline's sulfur dioxide emissions were extremely high compared to the 100% alcohol fuel because almost all oil products contain sulfur (**Figure 4**) (12). However, ethanol and methanol contain no sulfur, resulting in lower sulfur dioxide emission, this is also an advantage most plant-based fuels have over petroleum-based fuels (13).

An interesting observation is that hydrocarbon emissions varied independently of time, spiking at 2.5 minutes and falling back down at 1 and 5 minutes (**Figure 3**). This relationship was also seen in a study that measured the emissions of large gasoline pickup truck engines (14). The only difference between this study's data and our data was the spike occurred quicker in the cited study, at the 30-second mark (14).

Our results illustrate the large difference in emissions between E10 gasoline and 100% alcohol fuel. We demonstrated that 100% alcohol fuel generally produces less of the measured pollutants compared to E10 gasoline. The conversion to alcohol and emissions testing was performed on a 14-year-old gasoline lawn mower. The use of a 14-year-old lawn mower which likely had considerable wear on the cylinder walls and waning compression created variability, but this experiment serves to provide an example of how older gasoline lawn mowers that many people own can be converted to alcohol and demonstrates the drastic reduction in emissions this conversion can have.

Our study also utilized gasoline purchased from a commercial service station, which reduced variability in the experiment. This is in line with our goal to do a real-world comparison of a lawn mower running on widely available gasoline and used by most small engine operators. Purchasing specialty gasoline and blending it with ethanol in a laboratory setting would not provide a real-world comparison of widely available gasoline and alcohol fuel. The alcohol fuel, purchased from a hardware store, provided a real-world comparison as it is carried by a large amount of hardware

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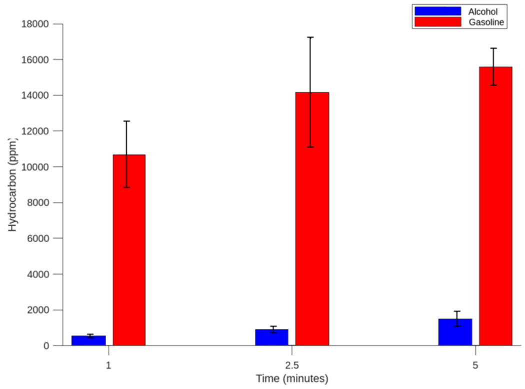

Figure 3: Comparison of hydrocarbon emissions. Difference in hydrocarbon emissions of two fuel sources, alcohol and E10 gasoline, when used as fuel for a small engine. Data is shown as mean ± SEM. Measurements of hydrocarbon in the exhaust were taken by inserting a probe at the 1, 2.5, and 5-minute marks for 30 seconds. These measurements constituted 1 trial; 5 trials were conducted for each fuel. The results of a two-sample t-test were all less than 0.005.

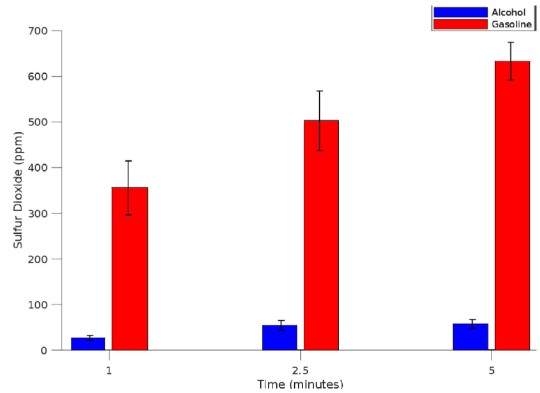

Figure 4: Comparison of sulfur dioxide emissions. Difference in sulfur dioxide emissions of two fuel sources, alcohol and E10 gasoline, when used as fuel for a small engine. Data is shown as mean ± SEM. Measurements of sulfur dioxide were taken by inserting a probe at the 1, 2.5, and 5-minute marks for 30 seconds. These measurements constituted 1 trial; 5 trials were conducted for each fuel. The results of a two-sample t-test were all less than 0.005.

stores and subsequently, provides an easily renewable fuel that is available, accessible, and affordable to a majority of people in the United States.

Our data indicates that an alcohol fuel purchased from and available at many hardware stores in the United States is a viable option for reducing small engine emissions. However, the study's results are based on one small engine that has been used for 14 years and has been modified to use alcohol fuel. Our study has demonstrated a strong correlation between 100% alcohol fuel and decreased emissions that warrants future work studying the effects of alcohol-based fuels on a wider range of small engines. Overall, our work provides the first step in creating a solution to the problem of small engine emissions.

MATERIALS AND METHODS

A Testo 350 portable emissions analyzer was used with CO_{low}, NO_{low}, NO_2, C_xH_y, and SO_2 sensors. These sensors were all manufactured by Testo and are accurate to ±5 % of the mean value. The lawn mower being tested was a Toro 6.5 horsepower push lawn mower model number 20016 from 2006. The engine attached to the lawn mower was a Tecumseh LV195EA, a 4-cycle overhead valve 195cc small engine. The lawn mower's carburetor jet was widened from a diameter of 0.024 inches to 0.032 inches using fine modeling drill bits. A second unmodified jet was purchased to be exclusively used when the lawn mower was running on gasoline.

The fuel system of the lawn mower was modified to incorporate two separate fuel tanks for each fuel (**Figure 5**). The fuel used was Klean Strip Denatured Alcohol Fuel and was purchased from a local hardware store. It is made up of approximately 50% methanol and 50% ethanol and contains no gasoline (9). The gasoline used was bought from a local service station and contained 10% ethanol.

To test the lawn mower emissions running on 100% alcohol and E10, 5 tests for each fuel were conducted. Each test began by filling the fuel tank that corresponds with that particular fuel. The lawn mower was then started and simultaneously a timer was started. When the timer reached one minute, the analyzer's probe was inserted into the muffler of the engine through a hole, and a measurement was taken every second for 30 seconds. This same procedure was repeated at 2.5 and 5 minutes. Each test resulted in an average for each gas measured – the 30 measurements were averaged into one value recorded on the Testo's internal memory and later downloaded onto a computer. In the experiment, a total of five tests for each fuel were conducted.

A two-sample t-test was used to test if the difference between emissions measurements taken at the same time interval but when using different fuels were statistically significant. For instance, sulfur dioxide was measured at the 1-minute interval 5 times while the engine was running on gasoline and 5 times while the engine was running on alcohol fuel. The 5 alcohol fuel values and 5 gasoline values at this time interval were then compared to each other. This same methodology was repeated for 1, 2.5, and 5-minute intervals for the 4 pollutants measured. A p-value less than 0.05 was taken as significant.

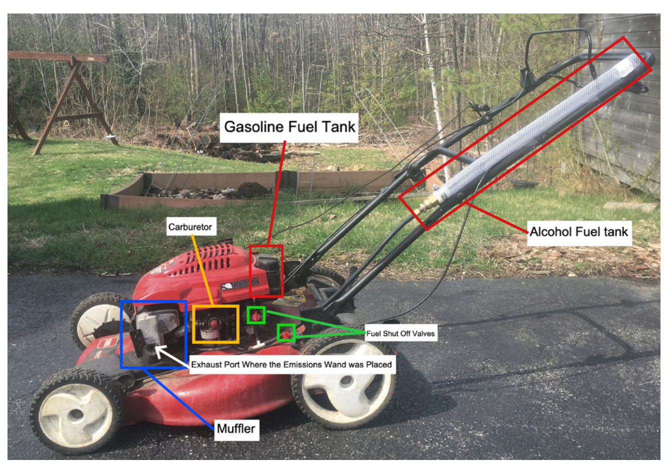

Figure 5: Alcohol and Gasoline Dual Fuel System. This fuel system was designed to minimize the risk of cross-contamination between gasoline and alcohol fuels. The shutoff valves ensure each fuel source can be isolated and the alcohol fuel tank's design allows for compressed air to be used to clear the fuel lines completely.

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