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NORTHWEST MISSOURI STATE UNIVERSITY

EFFECTS OF ETHANOL ON SMALL ENGINES AND THE ENVIRONMENT

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INTRODUCTION

With the support of the Missouri Corn Merchandising Council and the Department of Energy, Northwest Missouri State University conducted an applied research project to investigate the effects of the commercially available ethanol/gasoline fuel blend on small engines. The study attempted to identify any problems when using the 10% ethanol/gasoline blend in engines designed for gasoline and provide solutions to the problems identified. Fuel economy, maximum power, internal component wear, exhaust emissions and engine efficiency were studied.

PROCEDURE

Over the period of the project, the principal investigator was charged with the responsibility of selecting and procuring testing equipment, computer equipment and small engines. Testing equipment from three different vendors was purchased and connected to a computer so that all tests could be made simultaneously. The results of the tests were stored in the computer. Twenty-two vertical and horizontal crankshaft, single cylinder four-stroke engines, with 3 to 14 horsepower capacity, were tested. The effect of commercially available ethanol/gasoline blend (10% ethanol/90% gasoline) on small four-stroke cycle engines was studied. Adjustments were made to the engines during the tests in an attempt to improve the measured results. Adjustments made included setting governed no-load speed at manufacturers recommendation, load needle adjustment to maximize performance and reroute gasoline lines to prevent vapor lock.

The testing equipment consisted of:

- a. A dynamometer (water brake type 2 to 100 horsepower).
- b. Water valve to load dynamometer (remote controlled).
- c. Exhaust emissions tester (gases-hydrocarbons, oxygen, Carbon monoxide, carbon dioxide, nitrous oxide, sulfur dioxide).
- d. 740 Superflow Computer & computer program & connections.
- e. Computer, color printer/plotter.
- f. Shop constructed items: mounting stands for engines and the dynamometer, an exhaust mixing chamber & an intake to connect the air turbine.
- g. Gasoline turbine (.1 to 3 pounds per hour).
- h. Air turbine
- i. Temperature sensors for head, exhaust, intake air and room air.
- j. Barometer (barometric pressure).
- k. Sling psychrometer (used after each test to measure relative humidity).

Fuel economy, maximum power, internal component wear, exhaust emissions and engine efficiency were tested under the following test conditions:

- a. Engines tested had standard mufflers and standard air cleaners, as well as all other standard power-consuming devices.
- b. Engines were all new before testing.
- c. The engines were directly connected to a dynamometer by means of a flexible coupling. The engine's output shaft speed was used in computing the performance.
- d. The engines exhausted into a mixing chamber, during the test.
- e. There was no supplementary cooling or abnormal air blast into the air induction system or across the manifold, during the engine test.
- f. All tests were made with the carburetor inlet temperature within the range of minimum 5 degrees F. to maximum 125 degrees F.
- g. The dynamometer was calibrated using a lever arm and weights according to the manufacturer's recommendations, when it was hooked to the computer.
- h. Before testing the engines, the exhaust analyzer was calibrated using known gases.
- i. The speed was obtained using a 60 tooth wheel on the dynamometer and a magnetic pickup.
- j. All data was collected and stored on a computer.

Twenty-two new four-stroke cycle engines were tested. These engines were all single cylinder with 3 to 14 horsepower.

Six engines were from Kawasaki (four were 5 horsepower and two were 12 horsepower; all had vertical crankshafts).

Six engines were from Tecumseh (two were 3 horsepower, two were 5 horsepower and two were 12 horsepower). The two larger engines had vertical crankshafts and the other four had horizontal crankshafts.

Four engines were from Briggs and Stratton (two were 5 horsepower and two were 11 horsepower; all had horizontal crankshafts).

Six engines were from Kohler (two were 4 horsepower, two were 8 horsepower and two were 12 horsepower; all had horizontal crankshafts).

SMALL ENGINE TESTING PROCEDURE

1. The engine speed was controlled by the engine's governor and dynamometer load.
2. The engines were allowed to warm up to normal operating temperature prior to starting the engine tests. The maximum no-load speed was observed and altered if needed to meet the manufacturer's recommendation. The full load jet was adjusted, if needed, to get the maximum performance.

3. Like pairs of engines were tested (one on standard unleaded gasoline and one on standard commercial 10% ethanol/gasoline blend).
4. Performance data was taken every 10 seconds, before and while loading the engine, until it died. A small increase of load was applied after each line of data was taken. The running period at maximum horsepower was approximately 8.5 hours. Test data was collected approximately 8 times for each engine, or once each hour.
5. The simultaneous data collected were relative humidity, speed, torque, horsepower, induction air temperature, head temperature, ambient temperature, barometric pressure, fuel consumption, pounds of fuel/horsepower-hr., air intake volume, exhaust temperature, exhaust emissions (oxygen, carbon monoxide, carbon dioxide, nitrous oxide, sulfur dioxide, hydrocarbon).
6. After the engines were tested, they were all disassembled, inspected and measured for wear at critical points. (Measurements were taken when wear was observed, e.g. ring end gap). Carbon deposits were photographed in the combustion chambers and on the valve heads and stems.

STATISTICAL ANALYSIS

The following statistical treatment was performed on the data that was collected and stored in the computer.

This experiment was designed as a two level hierarchical experiment within a randomly assigned two factor cross classified factor. The factor of engines was treated as a randomly assigned replication. The analysis of variance was calculated with the factor of fuel type and engines being completely randomized and the other sources of variation nested under the individual engines. The hours of operation factor was nested under each individual engine used in the experiment. The performance curve observation factor was nested within an individual hour of operation within an individual engine.

The resulting data represented a single observation per cell for a point on the operational performance curve of an engine at a given hour of operation. The eight points on the performance curve were selected for differences in engine speed and the torque load the engine was under.

Source: D. V. Huntsberger, Elements of Statistical Inference Allyn and Bacon, Inc. 1961

The factors in the experiment which were found to be significant by the analysis of variance were analyzed using the Duncan Multiple Range F Technique for mean separation. Only significant main effects in the experiment were submitted to the above procedure.

The statistical analysis was done using the SAS System on a Vax 8565 Computer.

Source: SAS User's Guide: Statistics, SAS Institute, Inc. Cary, N.C. 1982

When interpreting the data in the tables, all differences that were considered significant were significant at the 1% error level unless indicated as being at the 5% level of error as shown in two tables.

RESULTS

The analysis of variance in Table 1 shows significant variations in carbon monoxide production due to fuel, engine type, fuel-engine type interaction, observation, engine type-observation interaction and fuel-observation interaction.

Table 1
Analysis of Variance Exhaust Carbon Monoxide (%)
Concentration in Small Engines.

Source	DF	Mean Square	F Value
FUEL	1	17.0236	23.77 **
ENGINE	10	432.8177	604.41 **
FUEL*ENGINE	10	90.1049	125.83 **
HOURL	7	7.5022	0.55 ns
ENGINE*HOURL	70	11.3494	0.83 ns
FUEL*HOURL	7	10.8355	0.79 ns
Within HOURL Error	70	13.6623	
OBS	7	12.3437	6.54 **
ENGINE*OBS	70	12.1108	6.41 **
FUEL*OBS	7	5.5386	2.93 **
HOURL*OBS	49	0.8550	0.45 ns
Within OBS Error	70	1.8885	
Error	1029	0.7160	
Total	1407		

** = Significant at the 1 % error level.
ns = Not Significant

The data in Table 2 shows some significant differences in the production of carbon monoxide due to engine type.

Table 2
Average Exhaust Carbon Monoxide (%) Level of
Small Engines tested and Duncan Ranking.

Engine Number	Carbon Monoxide (%)	
	Mean	Duncan Ranking (a)
6	7.31	A
9	7.16	A
3	6.55	B
10	6.41	B
4	6.40	B
2	6.01	C
8	5.94	C
1	4.67	D
7	2.82	E
11	2.60	F
5	2.56	F

a = Means with the same letter are not
significantly different.

Data in Table 3 shows a significant reduction of carbon monoxide due to using 10% ethanol instead of using regular unleaded gasoline. The average production of carbon monoxide was 5.20% when using 10% ethanol fuel compared to 5.42% carbon monoxide when using regular unleaded fuel.

Table 3
Effect of Fuel Type on Average Carbon
Monoxide (%) Level of Small Engines
tested and Duncan Ranking.

Fuel Type	Carbon Monoxide (%)	
	Mean	Duncan Ranking (a)
Ethanol	5.20	A
Regular	5.42	B

a = Means with the same letter are not
significantly different.

Data in Table 4 shows the variation in carbon monoxide percentages due to engine type using the different fuels. Without engine type 7 a greater difference in carbon monoxide percentages would have been shown.

Table 4
Effect of Fuel type on Average Exhaust
Carbon Monoxide (%) Level of Small
Engines tested.

Engine Number	Carbon Monoxide (%)	
	Regular	10% Ethanol
1	5.32	4.02
2	5.83	6.20
3	6.69	6.42
4	6.79	6.02
5	3.42	1.70
6	7.72	6.90
7	0.66	4.97
8	6.57	5.32
9	7.38	6.95
10	7.05	5.76
11	2.22	2.98
Average	5.42	5.20

Table 5 shows little if any variation in carbon monoxide production due to a greater load and the reduction of the speed of the engines throughout the sequential observations.

Table 5
Average Exhaust Carbon Monoxide (%) Level
of Small Engines tested, Duncan Ranking,
and average engine speed for each
sequential observations of engine
performance.

Sequential Observation	Carbon- Monoxide (%)	Duncan (a) Ranking
2	5.78	A
1	5.57	AB
3	5.42	BC
8	5.29	BCD
7	5.18	CD
4	5.18	CD
6	5.07	D
5	5.01	D

a = Means with the same letter are
not significantly different.

Table 6 shows some improvement in carbon monoxide level as the engines on 10% ethanol were loaded and their speeds were reduced.

Table 6

Average Exhaust Carbon Monoxide (%) Level of Small Engines tested and average engine speed of each sequential observations of engine performance for engines run on Regular and 10% Ethanol.

Sequential Observation	Regular		10% Ethanol	
	SPEED (rpm)	Carbon Monoxide (%)	SPEED (rpm)	Carbon Monoxide (%)
1	3427.7	5.63	3469.9	5.52
2	3269.6	5.64	3313.0	5.92
3	3096.9	5.27	3154.5	5.57
4	2921.1	5.31	2967.4	5.04
5	2717.5	5.28	2759.6	4.73
6	2510.5	5.37	2542.4	4.76
7	2170.7	5.44	2179.5	4.93
8	1725.2	5.44	1749.3	5.14

The analysis of variance in Table 7 shows significant variations in sulfur dioxide production due to fuel, engine type, fuel-engine type interaction, observation, engine type-observation interaction, fuel-observation interaction, and hour-observation interaction.

Table 7

Analysis of Variance Exhaust Sulfur Dioxide (parts per million) Concentration in Small Engines.

Source	DF	Mean Square	F Value
FUEL	1	21273.95	107.16 **
ENGINE	10	48065.50	242.10 **
FUEL*ENGINE	10	30098.71	151.61 **
HOUR	7	2524.26	0.39 ns
ENGINE*HOUR	70	4776.68	0.74 ns
FUEL*HOUR	7	2925.55	0.45 ns
Within HOUR Error	70	6451.10	
OBS	7	24256.31	33.34 **
ENGINE*OBS	70	4578.77	6.29 **
FUEL*OBS	7	2389.62	3.28 **
HOUR*OBS	49	219.25	0.30 ns
Within OBS Error	70	727.50	
Error	1029	198.52	
Total	1407		

** = Significant at the 1 % error level.

ns = Not Significant

Data in Table 8 shows some significant differences in sulfur dioxide production due to engine type.

Table 8
Average Exhaust Sulfur Dioxide (parts per million) Level
of Small Engines tested and Duncan Ranking.

=====		
Sulfur Dioxide (parts per million)		
Engine		
Number	Mean	Duncan Ranking (a)

11	79.3	A
2	78.2	A
3	64.3	B
6	62.5	B
4	54.5	C
9	44.5	D
10	41.1	DE
8	37.8	EF
1	35.7	F
5	32.0	G
7	19.5	H

a = Means with the same letter are not
significantly different.

Table 9 shows a significant difference in sulfur dioxide production due to fuel used. When using 10% ethanol fuel an average of 53.88 parts per million of sulfur dioxide was produced compared to 46.11 parts per million produced when using regular unleaded gasoline.

Table 9
Effect of Fuel Type on Average Sulfur
Dioxide (parts per million) Level of Small Engines
tested and Duncan Ranking.

=====		
Sulfur Dioxide (parts per million)		
Fuel		
Type	Mean	Duncan Ranking (a)

Ethanol	53.88	A
Regular	46.11	B

a = Means with the same letter are not
significantly different.

The difference would not have been so great without engine 7, as shown in Table 10, with its low output of sulfur dioxide using regular unleaded gasoline.

Table 10
Effect of Fuel type on Average Exhaust
Sulfur Dioxide (parts per million) Level of Small
Engines tested.

Engine Number	Sulfur Dioxide (parts per million)	
	Regular	10% Ethanol
1	41.54	30.04
2	56.57	99.98
3	72.87	55.78
4	56.28	52.73
5	45.34	18.82
6	56.42	68.67
7	6.28	32.73
8	42.20	33.56
9	41.09	47.90
10	47.62	34.65
11	40.96	117.82
Average	41.11	53.88

Table 11 shows a considerable reduction of sulfur dioxide production as the engines were beginning to be loaded.

Table 11
Average Exhaust Sulfur Dioxide (parts per million)
Level of Small Engines tested, Duncan
Ranking, and average engine speed for
each sequential observations of
engine performance.

Sequential Observation	Sulfur Dioxide (ppm)	Duncan (a) Ranking
1	66.70	A
2	64.83	A
3	58.77	B
4	48.51	C
5	42.84	CD
8	39.90	D
7	39.27	D
6	39.12	D

a = Means with the same letter are
not significantly different.

Table 12 shows the engines using 10% ethanol produced considerably more sulfur dioxide when they were running at high speed with no load.

Table 12

Average Exhaust Sulfur Dioxide (parts per million) Level of Small Engines tested and average engine speed of each sequential observations of engine performance for engines run on Regular and 10% Ethanol.

Sequential Observation	Regular		10% Ethanol	
	SPEED (rpm)	Sulfur Dioxide(ppm)	SPEED (rpm)	Sulfur Dioxide(ppm)
1	3427.7	59.63	3469.9	73.77
2	3269.6	56.42	3313.0	73.25
3	3096.9	50.69	3154.5	66.86
4	2921.1	43.69	2967.4	53.32
5	2717.5	40.51	2759.6	45.18
6	2510.5	38.15	2542.4	40.09
7	2170.7	39.53	2179.5	39.01
8	1725.2	40.23	1749.3	39.57

The analysis of variance in Table 13 shows significant variations due to fuel, engine type, fuel-engine type interaction, observation, and engine type-observation interaction.

Table 13

Analysis of Variance Exhaust Temperature F Concentration in Small Engines.

Source	DF	Mean Square	F Value
FUEL	1	254560.10	719.42 **
ENGINE	10	6082620.35	17190.17 **
FUEL*ENGINE	10	233738.59	660.57 **
HOUR	7	4655.86	1.03 ns
ENGINE*HOUR	70	5345.44	1.18 ns
FUEL*HOUR	7	7280.81	1.61 ns
Within HOUR Error	70	165007.58	
OBS	7	165007.58	201.15 **
ENGINE*OBS	70	26959.90	32.87 **
FUEL*OBS	7	419.34	0.51 ns
HOUR*OBS	49	989.98	1.21 ns
Within OBS Error	70	820.30	
Error	1029	353.84	
Total	1407		

** = Significant at the 1 % error level.

ns = Not Significant

Data in Table 14 shows a significant difference in exhaust temperatures between all engine types.

Table 14
Average Exhaust Temperature F of Small
Engines tested and Duncan Ranking.

Engine Number	Temperature F	
	Mean	Duncan Ranking (a)
9	910.4	A
11	898.4	B
10	753.1	C
8	712.1	D
5	634.5	E
1	620.8	F
7	565.6	G
6	524.3	H
4	357.7	I
3	351.8	J
2	246.3	K

a = Means with the same letter are not
significantly different.

Data in Table 15 shows engines using 10% ethanol had significantly higher exhaust temperatures. Engines burning 10% ethanol had an average exhaust temperature of 611.1 degree F. as compared to 584.3 degrees F. for engines using regular unleaded gasoline.

Table 15
Effect of Fuel Type on Average Exhaust
Temperature of Small Engines tested
and Duncan Ranking.

Fuel Type	Temperature F	
	Mean	Duncan Ranking (a)
Ethanol	611.1	A
Regular	584.3	B

a = Means with the same letter are not
significantly different.

Data in Tables 16 and 17 shows a progressive increase in exhaust temperatures as all the engines were progressively loaded, until they reached near stalling speeds.

Table 16

Average Exhaust Temperature Level of Small Engines tested, Duncan Ranking, and average engine speed for each sequential observations of engine performance.

Sequential Observation	Temperature	Duncan (a) Ranking
6	631.3	A
7	624.3	B
5	623.1	B
4	608.3	C
8	603.0	C
3	582.0	D
2	559.0	E
1	550.9	F

a = Means with the same letter are not significantly different.

Table 17

Average Exhaust Temperature of Small Engines tested and average engine speed of each sequential observations of engine performance for engines run on Regular and 10% Ethanol fuels.

Sequential Observation	Regular		10% Ethanol	
	SPEED (rpm)	Temperature	SPEED (rpm)	Temperature
1	3427.7	562.3	3469.9	539.4
2	3269.6	570.1	3313.0	547.8
3	3096.9	594.9	3154.5	569.0
4	2921.1	623.9	2967.4	592.7
5	2717.5	637.7	2759.6	608.4
6	2510.5	644.7	2542.4	618.0
7	2170.7	638.5	2179.5	610.0
8	1725.2	617.2	1749.3	588.8

The analysis of variance in Table 18 shows significant variations due to engine type, fuel-engine type interaction, observation, and engine type-observation interaction.

Table 18

Analysis of Variance of Fuel Consumption (pounds per hour) of Small Engines.

Source	DF	Mean Square	F Value
FUEL	1	0.5793	0.75 ns
ENGINE	10	359.0034	467.75 **
FUEL*ENGINE	10	29.7181	38.72 **
HOUR	7	1.3976	0.24 ns
ENGINE*HOUR	70	2.4841	0.42 ns
FUEL*HOUR	7	2.6801	0.46 ns
Within HOUR Error	70	5.8879	
OBS	7	37.7854	32.53 **
ENGINE*OBS	70	11.2117	9.65 **
FUEL*OBS	7	0.7985	0.69 ns
HOUR*OBS	49	0.6153	0.53 ns
Within OBS Error	70	1.1616	
Error	1029	0.7675	
Total	1407		

** = Significant at the 1 % error level.

ns = Not Significant

Data in Table 19 shows engines type 5 were a big consumer of fuel even though they produced the lowest horsepower.

Table 19

Average Fuel Consumption (pounds per hour) of Small Engines tested and Duncan Ranking.

Engine Number	Fuel Consumption (pounds per hour)	
	Mean	Duncan Ranking (a)
5	6.37	A
2	4.54	B
9	3.88	C
11	3.82	C
10	3.09	D
1	2.86	E
6	2.53	F
8	2.02	G
4	1.49	H
3	0.94	I
7	0.73	I

a = Means with the same letter are not significantly different.

Data in Table 20 shows no significant difference in the type of fuel used on fuel consumption. The average fuel consumption of the engines using 10% ethanol was 2.95 pounds per hour as compared to 2.91 pounds per hour for those using regular unleaded fuel.

Table 20
Effect of Fuel Type on Average Fuel Consumption of Small Engines tested and Duncan Ranking.

Fuel Type	Fuel Consumption (lb/hr)	
	Mean	Duncan Ranking (a)
Ethanol	2.95	A (no difference
Regular	2.91	A in the means)

a = Means with the same letter are not significantly different.

Data in Tables 21 and 22 shows the engines used the most fuel when the engines were being loaded and when they were running at high speed.

Table 21
Average Fuel Consumption of Small Engines tested, Duncan Ranking, and average engine speed for each sequential observations of engine performance.

Sequential Observation	Fuel Consumption	Duncan (a) Ranking
4	3.48	A
3	3.35	AB
2	3.26	AB
5	3.20	B
6	2.90	C
1	2.66	D
7	2.40	E
8	2.23	E

a = Means with the same letter are not significantly different.

Table 22

Average Fuel Consumption of Small Engines tested and average engine speed of each sequential observations of engine performance for engines run on Regular and 10% Ethanol fuels.

Sequential Observation	Regular		10% Ethanol	
	SPEED (rpm)	Fuel Consumption	SPEED (rpm)	Fuel Consumption
1	3427.7	2.75	3469.9	2.56
2	3269.6	3.22	3313.0	3.30
3	3096.9	3.25	3154.5	3.45
4	2921.1	3.43	2967.4	3.53
5	2717.5	3.26	2759.6	3.13
6	2510.5	2.88	2542.4	2.91
7	2170.7	2.32	2179.5	2.48
8	1725.2	2.20	1749.3	2.26

The analysis of variance in Table 23 shows significant variations in nitrous oxide production due to fuel, engine type, fuel-engine type interaction, observation, and engine type-observation interaction. It also shows significant variation at the 5% error level in nitrous oxide production due to fuel-observation interaction.

Table 23

Analysis of Variance of Exhaust Nitrous Oxide (parts per million) level of Small Engines.

Source	DF	Mean Square	F Value
FUEL	1	197743.32	26.95 **
ENGINE	10	4311706.51	587.55 **
FUEL*ENGINE	10	822375.65	112.06 **
HOURL	7	19249.45	0.21 ns
ENGINE*HOURL	70	74051.79	0.82 ns
FUEL*HOURL	7	67383.93	0.75 ns
Within HOURL Error	70	90184.02	
OBS	7	1753999.79	37.84 **
ENGINE*OBS	70	203895.59	4.40 **
FUEL*OBS	7	119360.97	2.57 *
HOURL*OBS	49	8728.52	0.19 ns
Within OBS Error	70	46355.62	
Error	1029	7338.47	
Total	1407		

** = Significant at the 1 % error level.

* = Significant at the 5 % error level.

ns = Not Significant

Data in Table 24 shows some significant differences in the production of nitrous oxide due to engine type.

Table 24

Average Exhaust Nitrous Oxide (parts per million) level of Small Engines tested and Duncan Ranking.

Engine Number	Nitrous Oxide (parts per million)	
	Mean	Duncan Ranking (a)
7	629.29	A
11	617.35	A
1	406.88	B
2	330.90	C
5	322.05	C
10	268.53	D
4	261.14	DE
3	244.43	E
6	206.14	F
9	109.46	G
8	43.27	H

a = Means with the same letter are not significantly different.

Data in Table 25 shows that engines using 10% ethanol produced significantly more nitrous oxide. The average production of nitrous oxide was 324.528 parts per million for engines using 10% ethanol as compared to 300.827 parts per million for engines using regular unleaded gasoline.

Table 25

Effect of Fuel Type on Average Exhaust Nitrous Oxide Level of Small Engines tested and Duncan Ranking.

Fuel Type	Nitrous Oxide (parts per million)	
	Mean	Duncan Ranking (a)
Ethanol	324.528	A
Regular	300.827	B

a = Means with the same letter are not significantly different.

Data in Table 26 indicates an exhaust analyzer malfunction for engine type 8 and maybe type 9. Without those 2 engine types the difference in average nitrous oxide produced would be very small comparing the 2 fuels used. This malfunction is also substantiated by the fact that the exhaust temperatures were normal for those 2 engine types. You would expect a very positive correlation between exhaust temperature and nitrous oxide production.

Table 26
Effect of Fuel type on Average Exhaust
Nitrous Oxide Level of Small
Engines tested.

Engine Number	Nitrous Oxide (parts per million)	
	Regular	10% Ethanol
1	248.140	565.625
2	386.937	274.859
3	238.312	250.546
4	212.406	309.875
5	233.781	410.328
6	263.953	148.328
7	762.484	496.093
8	0.000	86.546
9	53.109	165.812
10	260.234	276.828
11	649.734	584.968
Average	300.827	324.528

Data in Tables 27 and 28 shows a steady increase in nitrous oxide production as the engines were loaded and heated until they reached near their stalling speeds.

Table 27
Average Exhaust Nitrous Oxide Level of Small
Engines tested, Duncan Ranking, and average
engine speed for each sequential observations
of engine performance.

Sequential Observation	Nitrous Oxide (ppm)	Duncan (a) Ranking
7	404.49	A
6	402.65	A
8	394.23	A
5	372.84	AB
4	328.38	B
3	253.55	C
2	174.20	D
1	171.09	D

a = Means with the same letter are not significantly different.

Table 28

Average Exhaust Nitrous Oxide Level of Small Engines tested and average engine speed of each sequential observations of engine performance for engines run on Regular and 10% Ethanol fuels.

Sequential Observation	Regular		10% Ethanol	
	SPEED (rpm)	Nitrous Oxide (ppm)	SPEED (rpm)	Nitrous Oxide (ppm)
1	3427.7	179.17	3469.9	163.00
2	3269.6	180.89	3313.0	167.51
3	3096.9	279.84	3154.5	227.25
4	2921.1	332.44	2967.4	324.30
5	2717.5	343.76	2759.6	401.90
6	2510.5	357.15	2542.4	448.13
7	2170.7	372.29	2179.5	436.69
8	1725.2	361.04	1749.3	427.42

The analysis of variance in Table 29 shows significant variations due to fuel, engine type, fuel-engine type interaction, observation, engine type-observation interaction, and fuel-observation interaction.

Table 29

Analysis of Variance Engine Head Temperature F in Small Engines.

Source	DF	Mean Square	F Value
FUEL	1	1136.52	19.04 **
ENGINE	10	593821.80	9949.59 **
FUEL*ENGINE	10	66098.68	1107.49 **
HOURL	7	5083.58	1.14 ns
ENGINE*HOURL	70	5943.22	1.33 ns
FUEL*HOURL	7	1221.16	0.27 ns
Within HOURL Error	70	4473.64	
OBS	7	102290.00	541.73 **
ENGINE*OBS	70	2040.20	10.80 **
FUEL*OBS	7	560.73	2.97 **
HOURL*OBS	49	64.51	0.34 ns
Within OBS Error	70	188.82	
Error	1029	59.68	
Total	1407		

** = Significant at the 1 % error level.

ns = Not Significant

Data in Table 30 shows a significant difference between head temperatures of all engine types.

Table 30
Average Engine Head Temperature of Small
Engines tested and Duncan Ranking.

Engine Number	Head Temperature F	
	Mean	Duncan Ranking (a)
9	431.7	A
2	324.2	B
6	295.0	C
10	289.3	D
11	277.7	E
3	271.5	F
4	261.4	G
8	243.8	H
5	212.1	I
7	193.2	J
1	190.8	K

a = Means with the same letter are not
significantly different.

Data in Table 31 shows a significant difference between head temperatures of engines burning different fuels. Those engines burning 10% ethanol had an average head temperature of 272.8 degrees F. as compared to 271.0 degrees F. for engines burning regular unleaded gasoline.

Table 31
Effect of Fuel Type on Average Head
Temperature of Small Engines tested
and Duncan Ranking.

Fuel Type	Head Temperature F	
	Mean	Duncan Ranking (a)
Ethanol	272.8	A
Regular	271.0	B

a = Means with the same letter are not
significantly different.

Data in Tables 32 and 33 shows that head temperature continuously raised as more load was applied to all the engines.

Table 32

Average Engine Head Temperature of Small Engines tested, Duncan Ranking, and average engine speed for each sequential observations of engine performance.

Sequential Observation	Head Temperature F	Duncan (a) Ranking
8	309.3	A
7	297.8	B
6	285.0	C
5	275.1	D
4	264.4	E
3	252.6	F
2	245.7	G
1	245.4	G

a = Means with the same letter are not significantly different.

Table 33

Average Engine Head Temperature of Small Engines tested and average engine speed of each sequential observations of engine performance for engines run on Regular and 10% Ethanol Fuel.

Sequential Observation	Regular		10% Ethanol	
	SPEED (rpm)	Head Temperature F	SPEED (rpm)	Head Temperature F
1	3427.7	246.5	3469.9	244.2
2	3269.6	246.5	3313.0	244.9
3	3096.9	252.6	3154.5	252.6
4	2921.1	264.1	2967.4	264.7
5	2717.5	274.6	2759.6	275.5
6	2510.5	283.7	2542.4	286.4
7	2170.7	294.3	2179.5	301.2
8	1725.2	305.7	1749.3	312.8

The analysis of variance in Table 34 shows significant variation in carbon dioxide production due to fuel, engine type, fuel-engine type interaction, hour, observation, engine type-observation interaction, and fuel-observation interaction.

Table 34
Analysis of Variance Exhaust Carbon Dioxide Level
in Small Engines.

Source	DF	Mean Square	F Value
FUEL	1	89.6577	267.04 **
ENGINE	10	794.6443	2366.76 **
FUEL*ENGINE	10	101.3621	301.90 **
HOUR	7	24.1449	3.39 **
ENGINE*HOUR	70	9.6777	1.36 ns
FUEL*HOUR	7	6.6748	0.94 ns
Within HOUR Error	70	7.1219	
OBS	7	35.5168	23.69 **
ENGINE*OBS	70	8.7433	5.83 **
FUEL*OBS	7	5.8961	3.93 **
HOUR*OBS	49	0.4595	0.31 ns
Within OBS Error	70	1.4990	
Error	1029	0.3357	
Total	1407		

** = Significant at the 1 % error level.
ns = Not Significant

Data in Table 35 shows significant differences between carbon dioxide production of all engine types.

Table 35
Average Exhaust Carbon Dioxide Level of
Small Engines tested and Duncan Ranking.

Carbon Dioxide %		
Engine Number	Mean	Duncan Ranking (a)
7	12.16	A
8	10.90	B
9	10.40	C
2	8.00	D
11	7.38	E
6	7.08	F
1	6.60	G
10	6.38	H
4	6.16	I
3	5.52	J
5	3.96	K

a = Means with the same letter are not significantly different.

Data in Table 36 shows a significant difference between carbon dioxide production of engines burning different fuels. Those engines burning 10% ethanol produced an exhaust containing an average of 7.94% carbon dioxide as compared to exhaust from engines burning regular unleaded gasoline with an average of 7.43% carbon dioxide.

Table 36
Effect of Fuel Type on Average Exhaust Carbon Dioxide (%) of Small Engines tested and Duncan Ranking.

Fuel Type	Carbon Dioxide (%)	
	Mean	Duncan Ranking (a)
Ethanol	7.94	A
Regular	7.43	B

a = Means with the same letter are not significantly different.

Data in Table 37 shows engine types 7, 8, and 9 produced an excessive amount of carbon dioxide. These engine types produced very little sulfur dioxide or nitrous oxide as noted earlier.

Table 37
Effect of Fuel type on Exhaust Carbon Dioxide Level of Small Engines tested.

Engine Number	Carbon Dioxide (%)	
	Regular	10% Ethanol
1	5.05	8.16
2	7.07	8.93
3	4.83	6.21
4	5.97	6.34
5	3.22	4.70
6	8.63	5.53
7	13.18	11.14
8	10.42	11.39
9	9.92	10.88
10	5.82	6.93
11	7.65	7.11
Average	7.43	7.94

Data in Table 38 shows very little difference in carbon dioxide production due to hour of operation.

Table 38
Average Exhaust Carbon Dioxide Level of
Hours of Operation of Small Engines
tested and Duncan Ranking.

Hour of Operation	Carbon Dioxide %	
	Mean	Duncan Ranking (a)
5	8.17	A
8	7.88	AB
7	7.86	AB
3	7.85	AB
6	7.68	AB
4	7.63	AB
2	7.48	BC
1	6.92	C

a = Means with the same letter are not significantly different.

Data in Tables 39 and 40 shows some increase in carbon dioxide production between no load and loading the engines.

Table 39
Average Exhaust Carbon Dioxide of Small Engines
tested, Duncan Ranking, and average engine
speed for each sequential observations
of engine performance.

Sequential Observation	Carbon Dioxide (%)	Duncan (a) Ranking
5	8.06	A
6	8.06	A
7	7.96	A
4	7.90	A
8	7.89	A
3	7.61	B
2	7.10	C
1	6.90	C

a = Means with the same letter are not significantly different.

Table 40

Average Exhaust Carbon Dioxide of Small Engines tested and average engine speed of each sequential observations of engine performance for engines run on Regular and 10% Ethanol Fuel.

Sequential Observation	Regular		10% Ethanol	
	SPEED (rpm)	Carbon Dioxide (%)	SPEED (rpm)	Carbon Dioxide (%)
1	3427.7	6.81	3469.9	6.99
2	3269.6	7.08	3313.0	7.12
3	3096.9	7.58	3154.5	7.63
4	2921.1	7.65	2967.4	8.16
5	2717.5	7.67	2759.6	8.45
6	2510.5	7.63	2542.4	8.49
7	2170.7	7.54	2179.5	8.38
8	1725.2	7.50	1749.3	8.29

The analysis of variance in Table 41 shows significant variations in oxygen retention due to fuel, engine type, fuel-engine type interaction, observation, and engine type-observation interaction. It also shows significant variation at the 5% error level in oxygen retention due to fuel-hour interaction.

Table 41

Analysis of Variance Exhaust Oxygen Level in Small Engines.

Source	DF	Mean Square	F Value
FUEL	1	15.2222	149.56 **
ENGINE	10	688.7506	6767.03 **
FUEL*ENGINE	10	106.7696	1049.02 **
HOUR	7	2.2177	0.52 ns
ENGINE*HOUR	70	5.1113	1.21 ns
FUEL*HOUR	7	12.0847	2.85 *
Within HOUR Error	70	4.2400	
OBS	7	1.2674	5.19 **
ENGINE*OBS	70	1.8816	7.71 **
FUEL*OBS	7	0.1927	0.79 ns
HOUR*OBS	49	0.0934	0.38 ns
Within OBS Error	70	0.2441	
Error	1029	0.1017	
Total	1407		

** = Significant at the 1 % error level.

* = Significant at the 5% error level.

ns = Not Significant

Data in Table 42 shows a significant difference between exhaust oxygen retained due to engine type for most types of engines.

Table 42
Average Exhaust Oxygen Level of Small Engines
tested and Duncan Ranking.

Engine Number	Oxygen %	
	Mean	Duncan Ranking (a)
1	7.07	A
10	5.89	B
4	5.61	C
3	5.45	D
5	5.41	D
2	3.67	E
6	3.57	F
11	1.31	G
7	1.27	G
8	0.91	H
9	0.77	I

a = Means with the same letter are not
significantly different.

Data in Table 43 shows a significant difference between oxygen retention in the exhaust due to type of fuel used. Exhaust from engines using 10% ethanol retained an average of 3.62% oxygen compared to an average of 3.82 % oxygen retained in the exhaust of engines using regular unleaded gasoline.

Table 43
Effect of Fuel Type on Average Exhaust Oxygen
(%) of Small Engines tested and Duncan Ranking.

Fuel Type	Oxygen (%)	
	Mean	Duncan Ranking (a)
Ethanol	3.62	A
Regular	3.82	B

a = Means with the same letter are not
significantly different.

The analysis of variance in Table 44 shows significant variations in air flow due to fuel, engine type, fuel-engine type interaction, observation, engine type-observation interaction, and hour-observation interaction.

Table 44
Analysis of Variance of Air Flow (cubic feet per minute)
of Small Engines.

Source	DF	Mean Square	F Value
FUEL	1	2093.8132	454.04 **
ENGINE	10	6340.1007	1374.85 **
FUEL*ENGINE	10	863.3600	187.22 **
HOURL	7	83.1451	0.62 ns
ENGINE*HOURL	70	106.3219	0.79 ns
FUEL*HOURL	7	49.0843	0.36 ns
Within HOURL Error	70	134.8365	
OBS	7	2216.4227	94.86 **
ENGINE*OBS	70	134.5960	5.76 **
FUEL*OBS	7	30.6768	1.31 ns
HOURL*OBS	49	5.7286	0.25 **
Within OBS Error	70	23.3647	
Error	1029	4.6114	
Total	1407		

** = Significant at the 1 % error level.
ns = Not Significant

Data in Table 45 shows a significant difference in average air flow between all but 2 of the engine types.

Table 45
Average Air Flow (cubic feet per minute) of Small
Engines tested and Duncan Ranking.

Engine Number	Air Flow (cubic feet per minute)	
	Mean	Duncan Ranking (a)
9	32.7	A
11	23.6	B
10	20.3	C
1	19.2	D
2	17.9	E
8	16.7	F
5	13.6	G
6	12.6	H
3	10.0	I
7	10.0	I
4	9.2	J

a = Means with the same letter are not significantly different.

Data in Table 46 shows significantly more air used by engines burning 10% ethanol. Engines burning 10% ethanol used an average of 18.1 cubic feet per minute of air compared to the regular unleaded gasoline burning engines using an average of 15.7 cubic feet per minute.

Table 46
Effect of Fuel Type on Average Air
Flow of Small Engines tested
and Duncan Ranking.

Fuel Type	Air Flow (cubic feet per minute)	
	Mean	Duncan Ranking (a)
Ethanol	18.1	A
Regular	15.7	B

a = Means with the same letter are not significantly different.

Data in Tables 47 and 48 shows all the engines used more air as the loads started to increase and as the speeds began to decrease but the air flow decreased as the process continued.

Table 47
Average Air Flow (cubic feet per minute) of Small Engines tested,
Duncan Ranking, and average engine speed for
each sequential observations of engine
performance.

Sequential Observation	Air Flow (CFM)	Duncan (a) Ranking
5	20.2	A
4	20.0	A
6	19.4	AB
3	18.7	B
7	17.4	C
8	14.9	D
2	14.8	D
1	9.9	E

a = Means with the same letter are not significantly different.

Table 48

Average Air Flow (cubic feet per minute) of Small Engines tested and average engine speed of each sequential observations of engine performance for engines run on Regular and 10% Ethanol fuels.

Sequential Observation	Regular		10% Ethanol	
	SPEED (rpm)	Air Flow (CFM)	SPEED (rpm)	Air Flow (CFM)
1	3427.7	9.4	3469.9	10.3
2	3269.6	13.3	3313.0	16.3
3	3096.9	17.5	3154.5	19.9
4	2921.1	18.6	2967.4	21.3
5	2717.5	18.5	2759.6	22.0
6	2510.5	17.8	2542.4	20.9
7	2170.7	16.4	2179.5	18.5
8	1725.2	14.0	1749.3	15.8

The analysis of variance in Table 49 shows significant differences in pounds of fuel per horsepower-hour due to fuel, engine type, fuel-engine type interaction, observation, engine type-observation interaction, and fuel-observation interaction.

Table 49

Analysis of Variance of Fuel Flow (pounds per horsepower-hour)

Source	DF	Mean Square	F Value
FUEL	1	7.6511	14.84 **
ENGINE	10	105.6114	204.79 **
FUEL*ENGINE	10	8.7321	16.93 **
HOURL	7	1.0036	1.14 ns
ENGINE*HOURL	70	0.8789	1.00 ns
FUEL*HOURL	7	0.7481	0.85 ns
Within HOURL Error	70	0.8777	
OBS	7	59.2839	114.95 **
ENGINE*OBS	70	11.4541	22.21 **
FUEL*OBS	7	5.4383	10.55 **
HOURL*OBS	49	0.5392	1.05 ns
Within OBS Error	70	0.5101	
Error	1029	0.5157	
Total	1407		

** = Significant at the 1 % error level.
ns = Not Significant

Data in Table 50 shows a significant difference in pounds of fuel per horsepower-hour between some engine types.

Table 50

Average fuel flow (pounds per horsepower-hour) of Small Engines tested and Duncan Ranking.

Engine Number	Fuel Flow (pounds per horsepower-hour)	
	Mean	Duncan Ranking (a)
5	3.53	A
11	1.43	B
2	1.39	B
6	1.36	B
9	0.97	C
1	0.67	D
4	0.58	DE
8	0.56	DE
10	0.44	E
7	0.43	E
3	0.42	E

a = Means with the same letter are not significantly different.

Data in Table 51 shows a significant difference in pounds of fuel used per horsepower-hour. The engines using 10% ethanol used an average of 1.14 pounds of fuel per horsepower-hour as compared to the engines running on regular unleaded gasoline using an average of 1.00 pound of fuel per horsepower-hour.

Table 51

Effect of Fuel Type on Average Fuel Flow (pounds per horsepower-hour) of Small Engines tested and Duncan Ranking.

Fuel Type	Fuel Flow (pounds per horsepower-hour)	
	Mean	Duncan Ranking (a)
Ethanol	1.14	A
Regular	1.00	B

a = Means with the same letter are not significantly different.

CONCLUSION

After disassembling the engines, no significant wear was found in any of the engines. Some carbon build-up was found in all the engines, but no difference was found due to type of fuel used. All the oil was equally dirty in the engine pans.

All the carburetors were disassembled and inspected for deterioration of internal parts but no harm was found in any.

All engines started and ran on both types of fuel. Some were hard to restart when hot and some had problems with vapor locking, but neither of these problems could be tied to one kind of fuel more than the other. The 10% ethanol fuel appeared to have more vapor pressure in the storage containers during hot weather.

As concluded by the data, use of 10% ethanol fuel significantly reduced the carbon monoxide level in the exhaust.

There was a significant increase in the following due to using 10% ethanol fuel:

- a. hydrocarbons (parts per million)
- b. sulfur dioxide (parts per million)
- c. exhaust temperature (degrees F.)
- d. nitrous oxide (parts per million)
- e. head temperature (degrees F.)
- f. carbon dioxide (%)
- g. air flow or air consumption (cubic feet per minute)
- h. fuel used (pounds per horsepower-hour)

There was no significant difference in overall fuel consumption (pounds per hour) due to using either fuel.

There was a significant decrease in exhaust oxygen retained due to using 10% ethanol fuel.

It is therefore the conclusion of this investigator that the use of a 10% ethanol/gasoline blend fuel did not harm the small four-stroke cycle engines.