EMISSIONS AND DEMONSTRATION OF AN EMISSIONS CONTROL TECHNOLOGY FOR SMALL 2-STROKE UTILITY ENGINES

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Executive Summary

Small utility engines contribute to emission inventories in California that are disproportionately high on brake-specific basis (mass of pollutants produced per unit work performed). The California Air Resources Board (ARB) has established emissions standards for handheld and non-handheld equipment powered by these small utility engines. A number of technologies have the potential for meeting these emissions standards, including four-stroke engines, fuel-injected two-stroke engines, stratified scavenging two-stroke engines, and two-stroke engines with catalytic aftertreatment devices. Manufacturers, however, have expressed concerns about the ability to achieve the desired performance in a cost-effective way.

In an effort to add to our knowledge regarding emissions from two-stroke utility engines and to demonstrate a potential control technology, the University of California, Riverside, Bourns College of Engineering – Center for Environmental Research and Technology (CE-CERT) tested four small two-stroke utility engines: a 46 cc Tanaka (string trimmer), a 46 cc BKM-F1 modified Tanaka (string trimmer), a Stihl (string trimmer), and an Echo PB-210E (leaf blower). The unmodified Tanaka engine was tested as a baseline for the modified version, equipped with the BKM fuel/oil injection technology on an identical engine. The Stihl and Echo engines were tested in new condition and again after more than 100 operating hours. The program resulted in an assessment of emissions factors, fuel use, power, and durability for the engines tested. A summary of the results of this program is provided below.

- The BKM fuel/oil injection technology applied to the Tanaka two-stroke engine resulted in significant emissions reductions. The emission reductions were approximately 52% for carbon monoxide (CO), 70% for total hydrocarbons (THC), and 70% for particulate matter (PM). The BKM technology did result in nitrogen oxides (NO_x) emissions increasing by nearly 200%. The ARB emission standards, however, are written in terms of THC + NO_x. According to this metric, the BKM technology resulted in emission reductions in terms of THC + NO_x of 67%.

- The Echo engine was tested in new condition and after 100 hours of operation. Unfortunately, since this engine required maintenance during the course of accumulated operation, these emission results probably do not accurately reflect the absolute effects of the engine's deterioration on emissions. Specifically, this engine had lower emissions for CO and THC after operating for more than 100 hours, contrary to the expected emissions increase. The PM and NO_x emissions did increase after 100 hours of accumulated operation, but it is difficult to determine how much of these increases can be attributed to engine deterioration.

- The Stihl engine was tested in new condition and after 162 hours of operation. The results show significant increases in CO and PM emissions levels after hour accumulation compared with the new condition. Specifically, CO emissions increased by more than 200% while PM emissions increased by about 250%. There was a small (20%) increase in THC emissions after the accumulated hours, and a 64% reduction in NO_x emissions.

1. Introduction

Small utility engines (less than 20 horsepower [hp]) account for a disproportionate amount of emissions from the overall utility engine equipment category (per hp output). Large numbers of equipment using small utility engines — blowers, weed trimmers/edgers, and chain saws — operate with two-stroke gasoline-powered engines of 5 hp or less. Most are air-cooled; and few, if any, have emissions control equipment. Lawn and garden equipment, such as the types described above, and other small utility engines are the source of up to 5% of the nation's air pollution, according to estimates by the U.S. Environmental Protection Agency (EPA).[1]

The California Air Resources Board's first emissions control standards for these small utility engines were implemented in 1995, and a more stringent set of standards took effect in 2000. A number of technologies have the potential for meeting these more stringent levels, including four-stroke engines, fuel-injected two-stroke engines, stratified scavenging two-stroke engines, and two-stroke engines equipped with catalytic aftertreatment.[1,2,3,4] Manufacturers, however, have had concerns about the ability to achieve the desired performance in a cost-effective way.

BKM, Inc., has developed a prototype variable fuel/oil-injected engine design for a Tanaka 46 cubic centimeter (cc) utility engine, incorporating direct-gasoline-fuel-injection, a redesigned cylinder head that integrates the BKM injector, and a redesigned oiling system.[4] This technology was evaluated as part of this test program, as it represents a potential emissions control strategy for small two-stroke engines. The objective of this portion of the program was to evaluate the potential for new engine designs, such as the BKM model, in meeting current and near-term emissions standards. As part of this program, CE-CERT performed testing to determine the emission reduction potentials of the BKM technology by first evaluating a baseline Tanaka engine and then an identical engine equipped with the BKM system.

Additional concerns include whether the low emissions performance of these engines and control technologies can be maintained over their useful life. Wear and tear, poor maintenance, and uncharacteristic loads have been shown to dramatically affect emissions from two-stroke engines. To evaluate the effects of aging on two-stroke engines, CE-CERT acquired and tested a Stihl string trimmer engine and an Echo leaf blower engine in new condition. The engines were then placed into service with a commercial landscaping service for accumulation of at least 100 hours each. The same two engines were then retested at CE-CERT's laboratory facility for comparison of the engines in "aged" versus new condition.

2. Materials and Methods

2.1 Engine Tests

Four engines in total were tested as part of this program. They were a 46 cc Tanaka (string trimmer), a 46 cc BKM-F1 modified Tanaka (string trimmer), a Stihl (string trimmer), and an Echo PB-210E (leaf blower). The two Tanaka engines were identical except for the BKM modifications and were used to evaluate the potential emissions reductions resulting from the use of the BKM technology.

The Stihl and Echo engines were both "off the shelf" two-stroke engines. The purpose of testing these engines was to investigate the effects of engine deterioration on the emissions of two-stroke engines. These engines were tested in new condition and then again after a period of operating hours nearing the manufacturer-defined useful life (more than 100 hours for both engines).

Upon completion of baseline emissions testing, the Echo leaf blower and Stihl string trimmer were placed in the field with a professional landscaping company and operating hours were accumulated. At 40 hours, the Echo leaf blower engine was returned to BKM for maintenance because of poor engine idle performance (lean fuel condition). Testing at BKM showed the engine to be lean, especially at wide open throttle (WOT). The spark plug and air cleaner were removed and cleaned, and the carburetor was disassembled and blown out with compressed air. A new mixture of oil and gasoline was prepared. The engine was reassembled and tested. The engine was still slightly lean but demonstrated acceptable performance.

The landscaper declined the return of the blower, as he did not consider it to be a piece of professional landscaping equipment. Therefore, it was run at BKM (in outdoor conditions) for an additional 60 hours in order to achieve a total of 100 hours of running time.

The Stihl string trimmer was returned to BKM with 162 hours of accumulated operating time, and was still running reasonably well. No adjustments were made on this engine before re-testing at CE-CERT.

CE-CERT acquired the three commercially available engines and the modified engine from BKM. The ARB assisted with the selection, procurement, and aging criteria of this equipment.

2.2 Test Fuel

The test fuel used for this program was a certification fuel designed to meet the specifications of summertime California Phase II gasoline as outlined in the California Code of Regulations.[5] The test fuel properties remained consistent throughout the test program. Table 1 lists the general specifications for California Phase II gasoline.

Table 1
California Phase II Gasoline Specifications

	Flat Limit Standard	Average Standard	Cap for All Gasoline
RVP, psi	7.0	-	7.0
Sulfur, ppmw	40	30	80
Aromatic HC, vol%	25	22	30
Benzene, vol%	1.0	0.8	1.2
Olefins, vol%	6.0	4.0	10.0
Oxygen, wt%	1.8-2.2	--	1.8*-2.7
T90, deg F	300	290**	330
T50, deg F	210	200	220

* Wintertime only
** Refinery Cap = 310 °F

2.3 Exhaust Gas Sampling System

The exhaust gas measurement system used was a positive displacement pump-constant volume sampler (PDP-CVS). The system was consistent with requirements of the ARB small engine certification test protocol.[6] The system consisted of a dilution air filter, mixing zone and heat exchanger, positive displacement pump, pressure and temperature sensors. The dilution system was attached to the muffler with leak-free couplings. The exhaust line was of sufficient size to hold exhaust back pressure to a minimum. The exhaust sampling probe was located in the center section of the dilution tunnel, downstream of the mixing zone. The dilution air system was located in a temperature-controlled cell and air from this cell was used for the dilution air. The precision of the overall flow rates is within $\pm 1\%$ of the calibrated reading.

Throughout the course of each test, exhaust composition was measured using continuous analyzers. Emissions were sampled using standard techniques for exhaust measurement including a flame ionization detector (FID) for total hydrocarbon (THC) emissions, a chemiluminescence analyzer for oxides of nitrogen (NO_x) emissions and a non-dispersive infrared (NDIR) analyzer for carbon monoxide (CO) and carbon dioxide (CO_2).

Total particulate matter (TPM) results were determined using integrated gravimetric exhaust samples. The relative size fractions according to aerodynamic diameter for particles less than 10 μm in diameter (PM_{10}) and particles less than 2.5 μm in diameter ($PM_{2.5}$) were determined using a cascade impactor. A schematic of the sampling/analytical system is shown in Figure 1.

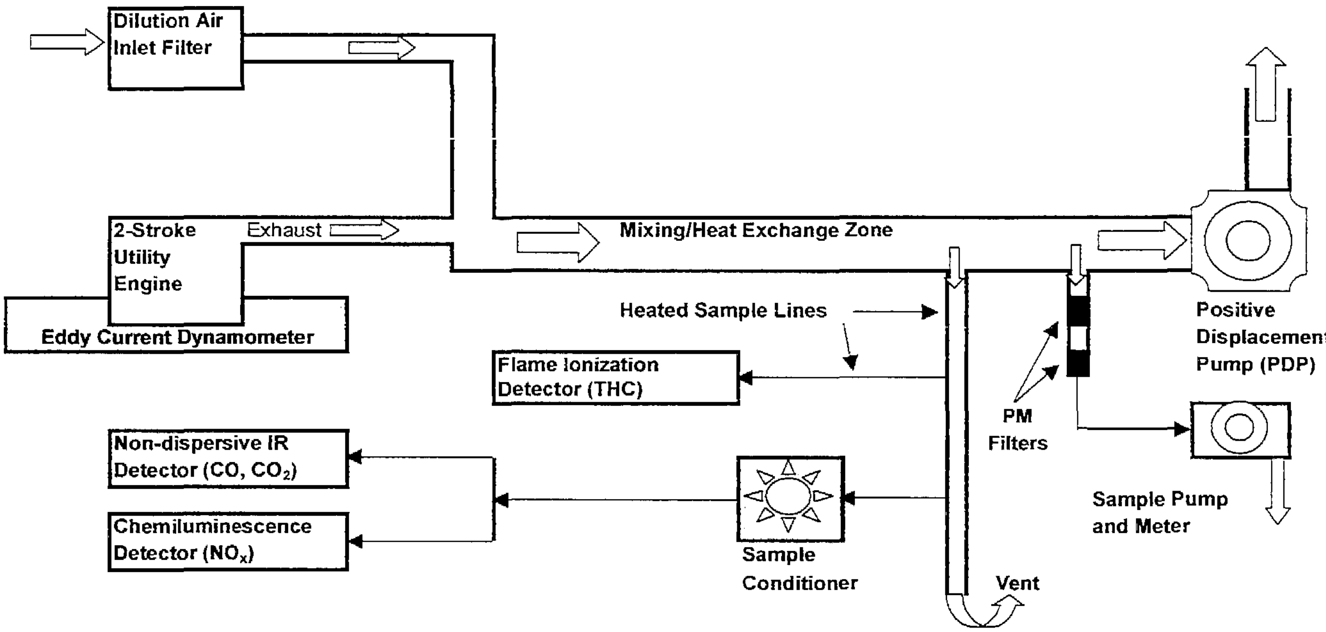

Figure 1
Small Utility Engine Emissions Testing System

2.4 Engine Test Procedures

1. Engine Preparation

Engine dynamometer tests were conducted using an eddy-current dynamometer provided by BKM Inc. In mounting the dynamometer, particular attention was exercised to ensure the engine was level and that the mounting configuration and the coupling to the dynamometer were correct. These procedures help prevent abnormal fuel distribution and fluctuations in fuel flow which could lead to fluctuations in emission levels.

Each engine tested was instrumented to measure exhaust emission levels, inlet air temperature, inlet air humidity, barometric pressure, fuel flow rate, engine speed, and engine brake torque output. The fuel-oil ratio for each engine was set according to the manufacturer's specifications.

2. Calibration and Preparation for Emissions Testing

Before each test, the engine dynamometer was calibrated and operated to verify performance and to verify the operation of the engine and its operation on the dynamometer. Each engine was mapped by BKM to determine the speed and power characteristics. A complete two-mode test in triplicate was conducted on each engine to determine the expected emission concentrations, fuel flow, and engine power output.

Emissions analyzer performance was verified, including checks for calibration drift, linearity, NO_2 to NO converter efficiency, and system bias. The calibration of the system was conducted using single blends of CO, CO_2, propane, and NO with either nitrogen or air as a diluent. All gases, including zero gas, met the analytical specifications for accuracy and allowable impurities specified in the ARB test procedures. Preliminary testing was conducted to establish the approximate emission levels of the engine.

In addition to emissions test data, information was obtained for each test regarding the test engine number, date and time of day, testing instrument operator, ambient temperature, humidity, and barometric pressure.

3. *Exhaust Emission Measurement Procedure*

a. Test Sequence

A sequence of two engine operating modes was employed for each test to provide an idle and full speed/full load-mapping of exhaust emissions. Emissions measurement data were recorded in each mode. The engines were operated in each mode for a stabilization period, followed by a sampling period of at least five minutes duration. The procedure was repeated twice to obtain triplicate samples. The throttle was locked in place for each specified throttle setting rather than running under a governed throttle condition. The test sequence, specified for small handheld equipment engines by the ARB test protocol, is shown in Table 2.

Table 2
Engine Operation Protocol
(Reference ARB Doc. # 92-02)

MODE	**1**	**2**
SPEED	**RATED SPEED**	**IDLE**
LOAD PERCENT	**100**	**0**
WEIGHTING (%)	**90**	**10**

NOTE: Where there was no rated speed given, the speed at maximum horsepower was used. The load was measured with the dynamometer. In these cases, full load was defined as the maximum load that could be applied at a given condition.

The testing was conducted in the following sequence:

- Operational checkouts and shakedown tests
- Baseline Tanaka 46-cc engine test and replicates
- BKM-modified Tanaka 46-cc engine test and replicates
- Echo PB-210 leaf blower engine test and replicates (new condition)
- Stihl FS80 string trimmer engine test and replicates (new condition)
- Echo PB-210 leaf blower engine test and replicates (aged condition)
- Stihl FS80 string trimmer engine test and replicates (aged condition)

2.5 Data Reporting

The emission factors were reported for each test for each pollutant (CO, THC, NO_x, CO_2, total particulate matter [TPM], and particle size fractions [PM_{10} and $PM_{2.5}$]). Emissions measurements were made on a molar basis with results given in terms of concentration. Conversion of concentrations into mass was based on the volumetric airflow rates in the dilution tunnel. The output of the blower frequency drive was continuously logged with the data acquisition system for subsequent conversion of emissions concentrations to mass flow rates.

Data validation was performed per United States Environmental Protection Agency (EPA) guidelines.[7,8] The emissions data for each of the engines tested were presented on individual spreadsheets. The spreadsheets include the reduced emissions data in both grams per hour and grams per brake horsepower hour for each measured pollutant in each of the two test modes of engine load setting. The final result on each spreadsheet shows the weighted-average emission factor for each engine tested in grams per brake horsepower-hour (g/bhp-hr).

3. Results and Discussion

Table 3 presents ARB emissions compliance certification limits for small (<65 cc displacement) utility engines for the years 1996-1999 and 2000-2005. The engines tested during the course of this program were all manufactured prior to the year 2000, and were required to meet the earlier set of standards. The current set of standards is presented for comparative purposes in evaluating the performance of the BKM CATS technology, as well as to "benchmark" the Echo and Stihl engines to gauge the extent of emissions reductions required to meet the current limits.

Table 3
ARB Certification Emissions Standards for Small (<65 cc displacement) Utility Engines [Years 1996 – 2005]

Year of Manufacture	Engine Displacement	Emission Limits (grams/brake Hp-hour)				
		THC	NO_x	THC + NO_x	CO	PM
1996 - 1999	< 50 cc	180.0	4.0	N/A	600.0	N/A
	50 - 65 cc	120.0	4.0	N/A	300.0	N/A
2000 - 2005	< 65 cc	N/A	N/A	54.0	400.0	1.5

N/A - Not Applicable

The emission factors associated with individual engines tested during this test program are presented in the following tables for each pollutant.

The data presented in Table 4 show results from emissions testing conducted on the "off the shelf" Tanaka 46 cc utility engine. Table 5 presents results from the identical Tanaka 46 cc engine modified with the BKM CATS technology. Figure 2 shows a comparison of the emissions of the baseline two-stroke Tanaka engine against those of the Tanaka engine modified by BKM. The baseline (unmodified) Tanaka engine met all Year 1996 – 1999 emission limits (CO, THC, and NO_x). It failed to meet any of the Year 2000 – 2005 criteria except for CO. The modifications made to the identical engine led to significant reductions of primary pollutant emissions. The emission reductions were approximately 52% for CO, 70% for THC, and 70% for PM compared with the baseline engine. Although NO_x emissions increased by nearly 200% using the BKM technology, there was still an emission reduction of 67% using the ARB regulatory metric of THC+NO_x. With the BKM modifications, the Tanaka engine meets the years 2000 -2005 emission requirements for CO and THC+NO_x. The PM emissions were only slightly above the year 2000 limits (1.7 vs. 1.5 g/hp-hr). It is anticipated that PM emissions can be further reduced with refinements to the technology.

Table 4
Baseline Tanaka 46 cc Utility Engine (unmodified)
Emissions Test Results

Measured Test Parameter	Modal Average Emission Rates (g/hr)			
	Mode 1	Mode 2	Overall Weighted Averages (g/hr)	Final Emission Factors (g/Hp-hr)
Power (Hp)	0.0	1.8		
THC	46.4	204.6	188.8	**116.5**
CO	32.9	336.3	305.9	**188.8**
CO_2	144.3	1274.7	1161.6	**716.8**
NO_x	0.2	2.5	2.3	**1.4**
THC + NOx	46.6	207.1	191.0	**117.9**
TPM	1.1	10.1	9.2	**5.7**
PM10			8.4	**5.2**
PM2.5			8.4	**5.2**

Table 5
Tanaka 46 cc Utility Engine Modified with BKM CATS Technology
Emissions Test Results

Measured Test Parameter	Modal Average Emission Rates (g/hr)			
	Mode 1	Mode 2	Overall Weighted Averages (g/hr)	Final Emission Factors (g/Hp-hr)
Power (Hp)	0.0	1.9		
THC	30.5	63.2	59.9	**34.6**
CO	17.6	173.7	158.1	**91.5**
CO_2	188.7	1274.7	1166.1	**674.6**
NO_x	0.2	7.9	7.1	**4.1**
THC + NOx	30.7	71.0	67.0	**38.8**
TPM	0.4	3.2	2.9	**1.7**
PM10			2.9	**1.7**
PM2.5			2.9	**1.7**

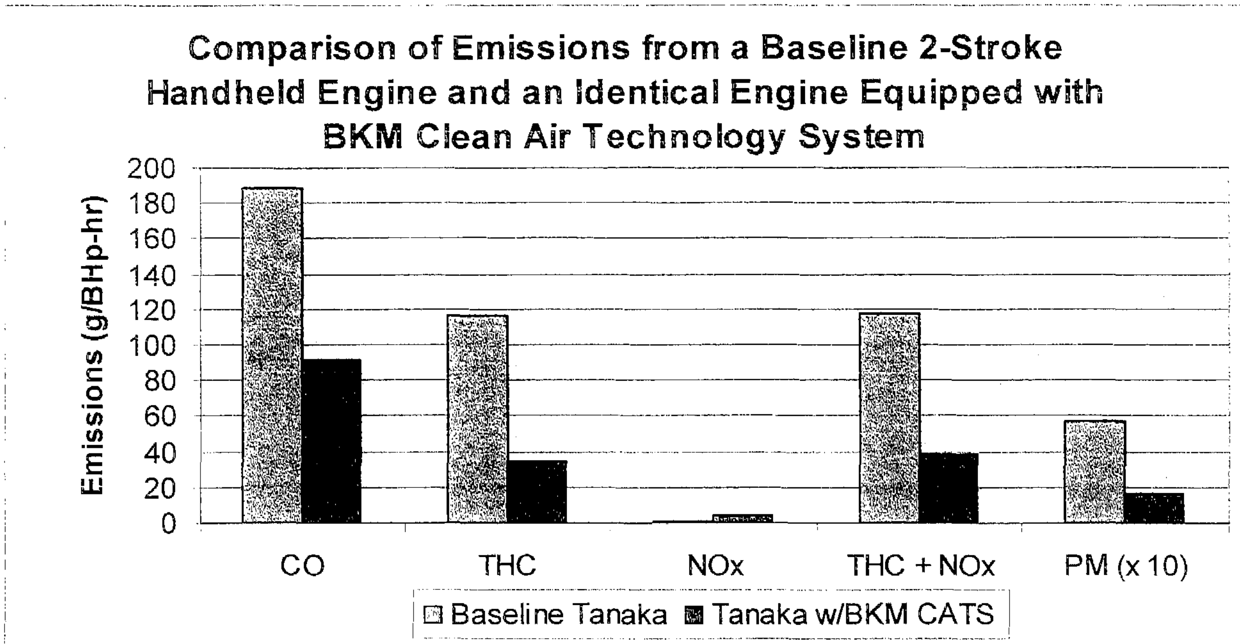

Figure 2
Emissions Comparison of 46 cc Tanaka Utility Engine
With and Without Emissions Control Technology

The results for the Echo engine in a new condition and after 100 hours of operation are presented in Tables 6 and 7, respectively, and Figure 3. In its new condition, the engine slightly exceeded the 1996 – 1999 limits for THC and CO by 3% and 13%, respectively. Only NO_x emissions were compliant with the earlier standards. Ironically, the engine did meet 2000 – 2005 limits for CO, but for no other pollutant. After 100 hours of operation, the engine met all CO limits, and 996 – 2000 THC and NO_x limits. Unfortunately, since this engine required maintenance during the course of its 100 hours of operation (as discussed in Section 2), these emission results probably do not accurately reflect the effects of engine deterioration on the emission rates. Specifically, this engine had significantly lower emissions of CO and THC after operation for 100 hours, in contrast to the expected increase in emissions due to engine wear. PM and NO_x emissions did increase after operation for 100 hours, but it is not possible with the given data to determine the proportion of the increase attributable to engine deterioration, and that which resulted from the engine adjustment.

Table 6
Echo PB-210E Utility Engine (new condition)
Emissions Test Results

Measured Test Parameter	Modal Average Emission Rates (g/hr)			
	Mode 1	Mode 2	Overall Weighted Averages (g/hr)	Final Emission Factors (g/Hp-hr)
Power (Hp)	0.0	1.1		
THC	20.5	131.0	120.0	**124.0**
CO	62.6	358.9	329.3	**340.4**
CO_2	196.4	1001.9	921.3	**952.3**
NO_x	0.0	0.8	0.7	**0.7**
THC + NOx	20.5	131.8	120.7	**124.7**
TPM	0.3	3.9	3.5	**3.7**
PM10			3.2	**3.3**
PM2.5			3.1	**3.3**

Table 7
Echo PB-210E Utility Engine (after 100 accumulated operating hours)
Emissions Test Results

Measured Test Parameter	Modal Average Emission Rates (g/hr)			
	Mode 1	Mode 2	Overall Weighted Averages (g/hr)	Final Emission Factors (g/Hp-hr)
Power (Hp)	0.0	1.0		
THC	15.4	89.9	82.4	**90.1**
CO	21.1	121.0	111.0	**121.3**
CO_2	150.5	825.2	757.7	**828.1**
NO_x	0.0	1.0	0.9	**1.0**
THC + NOx	15.4	90.8	83.3	**91.1**
TPM	0.2	6.4	5.8	**6.3**
PM10			5.7	**6.3**
PM2.5			5.7	**6.2**

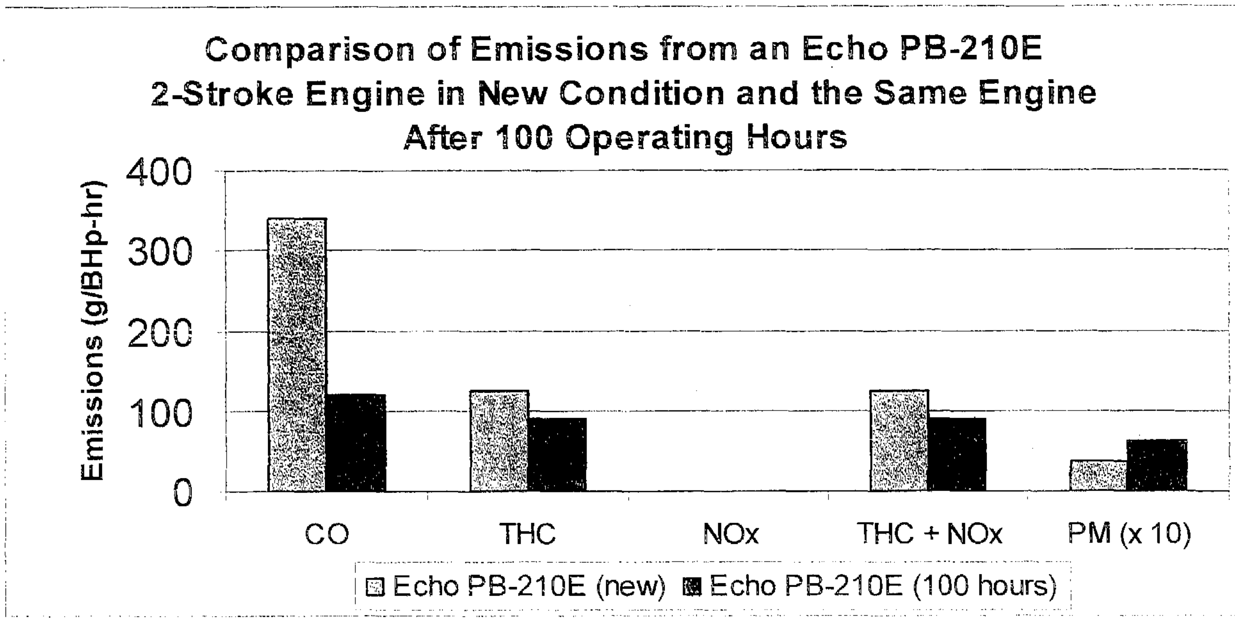

Figure 3
Emissions Comparison of Echo PB-210E Utility Engine for New and Used Operating Conditions

Testing results for the Stihl 2-stroke engine are shown in Tables 8 and 9, respectively, and Figure 4 for the new condition and after aging for 162 operating hours. In new condition, the engine met all of the 1996 – 1999 emission limits, and the 2000 – 2005 CO limits. After 162 operating hours, however, the engine exceeded the allowable 1996 – 1999 CO standards. The results show deterioration in the emissions levels after this period of operation for CO and PM. Specifically, CO emissions increased by more than 200% while PM emissions increased by 250%. There was a slight increase (~20%) in THC emissions from the used engine, and a 63% decrease in NO_x emissions. The THC+NO_x metric is 19% higher for the aged engine when compared the new conditions.

Table 8
Stihl FS80 Utility Engine (new condition)
Emissions Test Results

Measured Test Parameter	Modal Average Emission Rates (g/hr)			
	Mode 1	Mode 2	Overall Weighted Averages (g/hr)	Final Emission Factors (g/Hp-hr)
Power (Hp)	0.0	1.1		
THC	13.6	104.7	95.6	**98.8**
CO	2.0	153.4	138.2	**142.9**
CO_2	83.2	1080.3	980.6	**1013.6**
NO_x	0.0	1.2	1.1	**1.1**
THC + NOx	13.6	105.9	96.7	**99.9**
TPM	0.2	3.4	3.1	**3.2**
PM10			2.8	**2.9**
PM2.5			2.8	**2.9**

Table 9
Stihl FS80 Utility Engine (after 162 accumulated operating hours)
Emissions Test Results

Measured Test Parameter	Modal Average Emission Rates (g/hr)			
	Mode 1	Mode 2	Overall Weighted Averages (g/hr)	Final Emission Factors (g/Hp-hr)
Power (Hp)	0.0	0.9		
THC	10.2	107.1	97.4	**118.7**
CO	1.9	405.4	365.1	**444.6**
CO_2	67.2	730.0	663.8	**808.4**
NO_x	0.0	0.4	0.3	**0.4**
THC + NOx	10.2	107.5	97.8	**119.1**
TPM	0.2	10.4	9.4	**11.4**
PM10			9.4	**11.4**
PM2.5			9.3	**11.3**

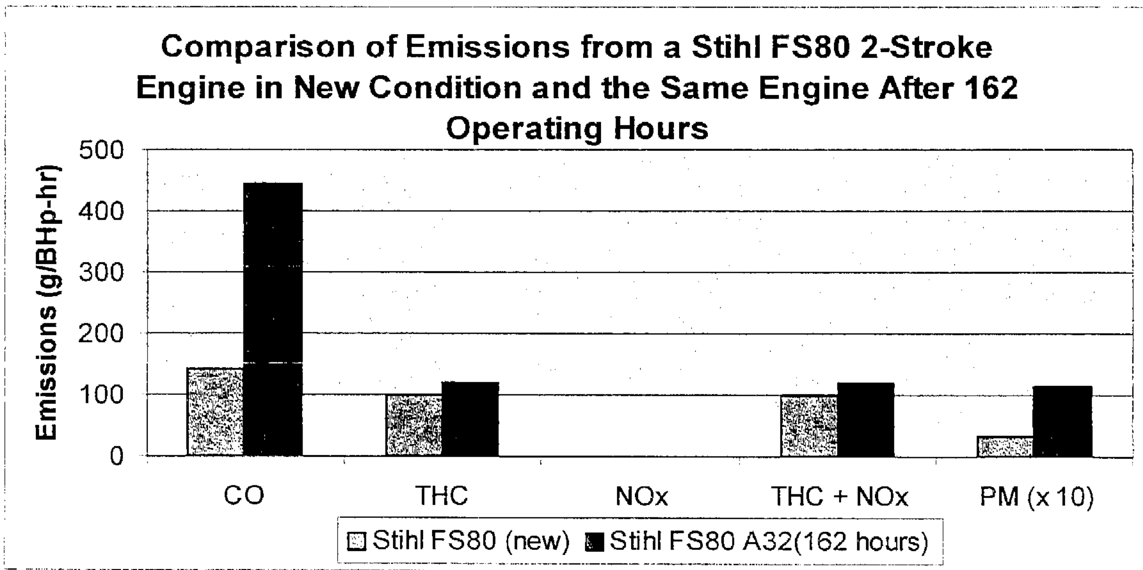

Figure 4
Emissions Comparison of Stihl FS80 Utility Engine for New and Used Operating Conditions

4. Summary and Conclusions

The University of California, Riverside, Bourns College of Engineering – Center for Environmental Research and Technology conducted emissions tests of four small two-stroke utility engines in order to assess effects of engine deterioration and to demonstrate a potential emissions control technology. Three engines were tested in a "new" condition to provide a benchmark for comparison. Two of these engines were then operated in typical applications (e.g. string trimmer, leaf blower) in order to accumulate significant hours of "wear and tear." An engine identical to the third engine was retrofit with a technology that provided separate variable control of oil injection, bypassing the traditional method of pre-mixing oil and fuel to provide lubrication and cooling to the small engines.

Two of the three "baseline" engines met or exceeded California Air Resources Board emission limits as applied to engines manufactured before 1999 and less than 65 cc in displacement. The third engine, although non-compliant, only slightly exceeded the allowable limits. None of the baseline engines, however, were able to meet all of the more stringent Year 2000-2005 limits. The particulate matter standard, implemented for the first time in the year 2000, appears to represent the biggest challenge for emissions compliance of small two-stroke engines. PM emission factors for the three baseline engines tested at CE-CERT were three to eight times the allowable year 2000 limits. The challenge for two-stroke engines is to maintain the lubricating and cooling properties of the fuel-oil premix while minimizing the PM contributing properties of the heavy oils.

One such strategy, developed by BKM, Inc., uses separate injection of fuel and oil into the combustion chamber. The system takes advantage of the fact that the amount of oil required for any given operating condition is a function of engine speed and load. At lower speeds and loads, less oil is injected with the gasoline. As demonstrated by testing at CE-CERT, the use of this technology resulted in substantial reductions of CO, THC, and PM. The 70% demonstrated reduction in PM emissions, however, was still slightly higher than the 2000 – 2005 PM emission limits of 1.5 g/bhp-hr.

An additional concern relates to engine deterioration over time. Results of this test program indicate increases in CO, THC, and PM emissions as operating hours are accumulated. Although the Echo engine results did not follow this trend, with higher emissions in the new vs. the "worn" condition, these results are probably more indicative of the maintenance and adjustments to the air/fuel ratio during the course of the accumulation of operating hours. This points to the critical importance of engine operating conditions on emissions. Slight changes in air, fuel, or oil ratios can have a dramatic effect on pollutant emissions in the exhaust.

In summary, there appear to be several promising strategies for reducing emissions from small two-stroke utility engines. One such strategy, using independent and variable fuel/oil injection with "smart" logic, can dramatically reduce emissions compared with an identical engine operating with the traditional pre-mixed fuel/oil strategy. The emissions reductions possible with this technology, however, may not be enough to meet increasingly lower emission limits set by regulatory agencies.

5. Recommendations

Two-stroke engines have provided power for a wide variety of applications for almost a century. They possess many inherent advantages, including a high torque to size ratio, the ability to operate without a cooling system, and the ability to operate effectively in harsh environments and applications, in spite of poor maintenance. The main disadvantage of the two-stroke engine, as demonstrated in this study and others, is the poor emissions performance.

Several options have been or are currently being explored by industry to address this problem. Advances in materials science and sophisticated tooling have made four-stroke engines more competitive in applications traditionally dominated by two-stroke engines. Although larger in size per power output than the two-strokes, the use of lighter and stronger materials has broadened the potential applications of four-stroke engines.

Other potential emission control strategies for two-stroke engines, not covered in the current study, should be explored in order to maximize the choices and flexibility of end-users of small utility engines. We highly recommend further study of fuels and lubricants, some of which may provide significant emissions benefits with minimal incremental costs. It is obvious from the BKM CATS technology demonstration that the amount of lubricating oil injected into the combustion chamber of engines is directly related to the mass and composition of emissions in the exhaust. It is likewise reasonable to assume that the chemical and physical properties of the oils (and the fuels for that matter) used in two-stroke engines may also bear a direct relationship to emissions.

Another strategy worth exploring includes engine modifications such as stratified scavenging techniques, dynamic modeling and design of combustion chambers, variable injection/ignition, and high-pressure injection, to name a few. Some of these techniques can be applied to directly reduce emissions, while others indirectly reduce emissions by increasing efficiency.

Finally, there have been major advances in aftertreatment technologies that are now being applied to very non-traditional sources, such as diesel engines and charbroiler exhaust. It is reasonable to assume that an effective catalytic control device, combined with novel heat transfer strategies, could be applied to two-stroke engine exhaust.

Major efforts are required to accomplish these goals. We are confident that such efforts will lead to two-stroke engines that can meet the most stringent emissions limits. Without a concerted effort from industry and regulatory agencies, the two-stroke engine will quickly become an endangered species.

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Appendix. Emission Test Results for the Baseline Tanaka Engine

3-TEST AVERAGES
Baseline Tanaka 46 cc Engine

Mode 1 Idle/no load	Torque (ft-lb)	Speed (rpm)	THC (ppm)	CO (ppm)	CO_2 (%)	NO_x (ppm)	TPM (mg/dscf)
	0.00	2650.00	260.80	92.53	0.03	0.31	0.108
Mode 2 **full speed/full load**	**Torque (ft-lb)**	**Speed (rpm)**	**THC (ppm)**	**CO (ppm)**	**CO2 (%)**	**NOx (ppm)**	**PM (mg/dscf)**
	1.35	7000.00	1143.61	941.41	0.23	4.22	0.944

mode	flow rate (dscfm)	PM sample volume (dscf)	filter 1 initial weight (mg)	filter 1 final weight (mg)	filter 2 initial weight (mg)	filter 2 final weight (mg)	total PM mass (mg)
1	176.54	7.328	112.269	112.948	115.508	115.617	0.788
2	177.445	7.423	115.252	122.108	117.631	117.784	7.009

PM10 fraction	PM2.5 fraction
0.922	0.92

Sample Calculations

Mode 1 PM mass emission rate

= [PM concentration (mg/dscf)] x [flow rate (dscfm)] x [60 min/hr] x [g/1000 mg]
= [0.108] x [176.54] x 60 / 1000
= **1.14 g/hr**

Mode 1 THC mass emission rate

= [1.583 x 10-7] x [flow rate (dscfm)] x [MW] x [concentration (ppm)] x [454 g/lb]
= [1.583 x 10-7] x [176.54] x [14.0268] x [260.8] x [454]
= **46.4 g/hr**

weighted average THC mass emission rate

= 10% x [Mode 1 (g/hr)] + 90% x [Mode 2 (g/hr)]
= 0.1 x [46.4] + 0.9 x [204.6]
= **188.75 g/hr**

Mode 2 Horsepower = [Mode 2 torque (ft-lb)] x [Mode 2 speed (rpm] / 5252
= [1.351] x [7000] / 5252
= **1.80 Hp**

THC Emission Factor = [weighted average emission rate (g/hr)] / [weighted average horsepower (Hp)]
= [188.75] / [1.80]
= **116.5 g/Hp-hr**

Emission Test Results for the Tanaka Engine with BKM CATS Technology

3-TEST AVERAGES
Tanaka 46 cc Engine w/BKM CATS

Mode 1 Idle/no load	Torque (ft-lb)	Speed (rpm)	THC (ppm)	CO (ppm)	CO2 (%)	NOx (ppm)	PM (mg/dscf)
	0.000	2500.000	161.850	46.741	0.032	0.284	0.031
Mode 2 full speed/full load	Torque (ft-lb)	Speed (rpm)	THC (ppm)	CO (ppm)	CO2 (%)	NOx (ppm)	PM (mg/dscf)
	1.441	7000.000	344.500	474.587	0.222	13.120	0.296

mode	flow rate (dscfm)	PM sample volume (dscf)	filter 1 initial weight (mg)	filter 1 final weight (mg)	filter 2 initial weight (mg)	filter 2 final weight (mg)	total PM mass (mg)
1	186.79	0.227	7.242	114.321	114.459	113.624	113.713
2	181.85	2.2	7.427	112.131	114.242	115.213	115.302

PM10 fraction	PM2.5 fraction
1	1

Emission Test Results for the New Echo Leaf Blower Engine

3-TEST AVERAGES
Echo PB-210E Engine (New)

Mode 1 Idle/no load	Torque (ft-lb)	Speed (rpm)	THC (ppm)	CO (ppm)	CO2 (%)	NOx (ppm)	PM (mg/dscf)
	0.000	2721.000	336.887	514.360	0.103	0.131	0.081
Mode 2 full speed/full load	Torque (ft-lb)	Speed (rpm)	THC (ppm)	CO (ppm)	CO2 (%)	NOx (ppm)	PM (mg/dscf)
	0.865	6527.000	745.171	1022.156	0.182	1.344	0.372

mode	flow rate (dscfm)	PM sample volume (dscf)	filter 1 initial weight (mg)	filter 1 final weight (mg)	filter 2 initial weight (mg)	filter 2 final weight (mg)	total PM mass (mg)
1	60.43	0.597	7.328	112.269	112.757	115.508	115.617
2	174.44	6.284	16.876	115.252	121.383	117.631	117.784

PM10 fraction	PM2.5 fraction
0.9	0.89

Emission Results for the Echo Leaf Blower Engine After 100 Operating Hours

3-TEST AVERAGES
Echo PB-210E Engine (Aged for 100 hours)

Mode	Torque (ft-lb)	Speed (rpm)	THC (ppm)	CO (ppm)	CO2 (%)	NOx (ppm)	PM (mg/dscf)
Mode 1 Idle/no load	0.000	2711.471	263.252	180.785	0.082	0.227	0.071
Mode 2 full speed/full load	0.819	6515.765	510.149	343.972	0.149	1.693	0.607

mode	flow rate (dscfm)	PM sample volume (dscf)	filter 1 initial weight (mg)	filter 1 final weight (mg)	filter 2 initial weight (mg)	filter 2 final weight (mg)	total PM mass (mg)
1	57.95	0.516	7.266	114.509	115.113	112.862	112.774
2	174.75	9.76	16.066	115.299	124.88	116.919	117.098

PM10 fraction	PM2.5 fraction
0.997	0.992

Emission Test Results for the New Stihl String Trimmer Engine

3-TEST AVERAGES
Stihl FS80 Engine (New)

Mode	Torque (ft-lb)	Speed (rpm)	THC (ppm)	CO (ppm)	CO2 (%)	NOx (ppm)	PM (mg/dscf)
Mode 1 Idle/no load	0.000	2721.000	722.384	52.727	0.141	0.154	0.146
Mode 2 full speed/full load	0.865	6527.000	753.263	552.540	0.248	2.653	0.414

mode	flow rate (dscfm)	PM sample volume (dscf)	filter 1 initial weight (mg)	filter 1 final weight (mg)	filter 2 initial weight (mg)	filter 2 final weight (mg)	total PM mass (mg)
1	18.71	0.684	4.682	116.642	117.265	114.743	114.804
2	137.88	6.156	14.864	113.683	119.697	114.858	115

PM10 fraction	PM2.5 fraction
0.9	0.89

Emission Results for Stihl String Trimmer Engine After 160 Operating Hours

3-TEST AVERAGES
Stihl FS80 Engine (Aged for 162 hours)

	Torque (ft-lb)	Speed (rpm)	THC (ppm)	CO (ppm)	CO2 (%)	NOx (ppm)	PM (mg/dscf)
Mode 1 Idle/no load	0.000	1989.824	544.910	50.403	0.115	0.268	0.159
Mode 2 full speed/full load	0.734	6524.118	499.882	947.309	0.109	0.534	0.814

mode	flow rate (dscfm)	PM sample volume (dscf)	filter 1 initial weight (mg)	filter 1 final weight (mg)	filter 2 initial weight (mg)	filter 2 final weight (mg)	total PM mass (mg)
1	18.53	1.061	6.682	115.687	116.731	114.469	114.486
2	212.61	15.557	19.106	113.033	128.55	117.767	117.807

PM10 fraction	PM2.5 fraction
0.999	0.9921