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Emissions profile from new and in-use handheld, 2-stroke engines

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Abstract

The objective of this study was to characterize exhaust emissions from a series of handheld, 2-stroke small engines. A total of 23 new and used engines from model years 1981–2003 were studied; these engines spanned three phases of emission control (pre-control, phase-1, phase-2). Measured emissions included carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxides (NO_x), hydrocarbons (HC), fine particulate matter (PM_{2.5}), and sulfur dioxide (SO₂). Emissions reductions in CO (78%) and HC (52%) were significant between pre-control and phase-2 engines. These reductions can be attributed to improvements in engine design, reduced scavenging losses, and implementation of catalytic exhaust control. Total hydrocarbon emissions were strongly correlated with fuel consumption rates, indicating varying degrees of scavenging losses during the intake/exhaust stroke. The use of a reformulated gasoline containing 10% ethanol resulted in a 15% decrease in HC and a 29% decrease in CO emissions, on average. Increasing oil content of 2-stroke engine fuels results in a substantial increase of PM_{2.5} emissions as well as smaller increases in HC and CO emissions. Results from this study enhance existing emission inventories and appear to validate predicted improvements to ambient air quality through implementation of new phase-2 handheld emission standards.

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1. Introduction

Many people use small, handheld, gasoline-powered, spark-ignition engines on a regular basis for lawn and garden work. These small engines

(used in applications such as string trimmers, chain saws, and leaf blowers) emit a variety of pollutants, including carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons (HC), and particulate matter (PM) into the atmosphere. The 2002 EPA national emissions trends document indicates that HC and CO emissions from these engines accounted for roughly 10.5% and 4.8% of total US emissions, respectively (EPA, 2005). Individuals who operate these engines on a regular basis undergo disproportionately high exposures to these pollutants

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(Bunger et al., 1997). The US EPA began regulating small engine emissions of CO, NO_x, and HC in 1997 as part of the phase 1 rulemaking process (EPA, 2000b). Handheld small engines are classified according to their engine displacement: class III engines have a displacement less than 20 cm³, class IV engines have displacement between 20 and 50 cm³, and class V engines have a displacement greater than 50 cm³. EPA's phase 2 rulemaking calls for a graduated phase-in of emission standards beginning in 2002 and completing in 2007. All class III and IV engines must emit less than 805 g kW h⁻¹ of CO and less than 50 g kW h⁻¹ for the sum of HC+NO_x by the 2005 model year. For class V engines, emissions of CO must not exceed 603 g kW h⁻¹ and HC+NO_x must not exceed 72 g kW h⁻¹ by model year 2007 (EPA, 2000b). Since these regulations are phased in over a period of several years, EPA regulates these engines according to their model year. *Pre-control* engines represent all class III and IV engines built before 1997, and class V engines built before 1998. *Phase-1* engines represent model years 1997–2001 for class III and IV and model years 1998–2003 for class V engines. All newer engines, after 2001 for class III, IV and after 2003 for class V, are designated as *Phase-2*. Because the phase 2 standards are phased in over a period of years, some engines designated as “phase 2” do not comply with the final standards (i.e., 50 g kW h⁻¹ HC+NO_x for class III and IV) during the phase-in period.

EPA estimates that the newer phase-2 standard will result in a 70% reduction in annual HC+NO_x emissions from handheld engines compared to phase-1 levels, by the year 2027. EPA's current data are rather limited for estimating the contribution of small, spark-ignition engines to the mobile source inventory for PM, air toxics, and regulated gases (HC, CO, and NO_x). Furthermore, the in-use fleet contains a variety of pre-control, phase-1, and phase-2 engines. The objective of this study, therefore, was to characterize emissions from a variety of small, handheld, spark ignition, 2-stroke engines to validate emission estimates for this important non-road mobile source category. A secondary objective was to determine the effects of different oil and fuel blends on these emissions. This objective is meant to address the recent increased use of ethanol-containing fuels and synthetic oils in the transportation sector. A third objective was to assess the industry response to the phase-2 rulemaking via advances in engine design and

control in order to meet these new regulatory requirements.

2. Materials and methods

A total of 23 spark-ignition engines from model years 1987–2003 were tested in this study: 18 were local, in-use engines and five were new. The used engines (12 string trimmers and six chain saws) were obtained locally from consumers, pawn shops, and lawn service vendors. The new engines (three string trimmers, one chain saw, and one blower) were loaned from the Outdoor Power Equipment Industry (OPEI) through EPA's Office of Transportation and Air Quality. Specific details on each engine are provided in Table 1. All engines were tested “as is”, with minimal (if any) maintenance performed to get them to run properly on the dynamometer. As these engines were not chosen randomly, their representativeness to the entire source category population cannot be determined.

2.1. Dynamometer setup

Engine testing was conducted at EPA's Small Engine Test Facility, located in Research Triangle Park, North Carolina. For this study, a test stand rated for dynamometers up to 16 hp (LA Research and Engineering Inc., Theodore, AL) was mounted on a steel bed plate (20'L × 5'W × 6"H) to ensure engine stability. Test engines were coupled to eddy-current dynamometers (2WB43-4 hp, 2WB65-16 hp, Vibro-Meter Inc., Manchester, NH) that provided a prescribed engine-loading over the emissions test. Two different dynamometers were used: one for the smaller string trimmers rated from 0.26 to 1.1 hp, and one for the larger chain saws rated from 1.41 to 3.34 hp. The dynamometer was equipped with a strain gauge for torque measurement (BLC-3030025, Vibro-Meter Inc., Manchester NH) and a magnetic field-depending resistor to measure engine speed in rotations per minute (rpm). Engines were tested while operating the dynamometers in the “torque” mode, which provided a constant resistive load to the engine, regardless of engine speed. The resistive load was set by varying the excitation current to the eddy-current dynamometer. Engine speed (in rpm) was maintained at the desired level by adjusting the engine throttle position with a computer-controlled actuator.

Engines were tested using the composite two-mode (C2M) 10-min duty cycle with the exception

Table 1
Description of engines tested

	Engine ID	Model year ^a	Engine type ^b	Displacement (cm ³)	Engine class	Power (hp)	Speed (rpm)	Torque (ft-lbs)	Engine source
Pre-control	1	1989	S	21	IV	0.48	6800	0.38	Homeowner
	2	1987	S	25	IV	0.27	6800	0.21	Homeowner
	3	1991	S	17	III	0.33	6800	0.25	Homeowner
	4	Unknown	C	45	IV	1.41	7400	1.00	Homeowner
	5	1998	S	31	IV	0.65	6800	0.50	Previous study
	6	1996–1997	S	24	IV	0.55	6800	0.43	Homeowner
Phase 1	7	1998	C	36	IV	1.84	8000	1.20	Pawn shop
	8	1998–1999	S	25	IV	0.65	6800	0.50	Pawn shop
	9	1999	S	25	IV	0.71	6800	0.55	Pawn shop
	10	1999	S	25	IV	0.66	6800	0.50	Rental
	11	1999	S	25	IV	0.77	6800	0.60	Rental
	12	1999	C	51	V	3.02	9000	1.75	Pawn shop
	13	2000	S	18	III	0.26	6800	0.20	Homeowner
	14	2001	S	25	IV	0.55	6800	0.43	Pawn shop
	15	2001	S	32	IV	0.73	6800	0.55	Pawn shop
Phase 2	16	2002	C	45	IV	1.92	8750	1.15	Pawn shop
	17	2002	C	42	IV	1.95	8500	1.20	Pawn shop
	18	2002	C	59	V	3.34	9500	1.85	Pawn shop
	19	2003	S*	25	IV	1.02	8500	0.63	OPEI ^c
	20	2003	S*	25	IV	1.01	9000	0.58	OPEI
	21	2003	C*	32	IV	1.62	8500	1.00	OPEI
	22	2003	B*	57	V	2.85	7533	1.98	OPEI
	23	2003	S ^d	25	IV	1.10	7500	0.77	OPEI

^aIn general, model years before 1997 are designated as ‘Pre-control’ engines, 1997–2001 as ‘Phase-1’, and after 2002 as ‘Phase-2’.

^bType S = string trimmer, type C = chain saw, type B = blower, * = catalyst equipped.

^cOutdoor Power Equipment Institute (OPEI).

^dThis engine is a ‘hybrid’ 4-cycle engine designed to run on 2-cycle engine fuel.

of chain saws, which were tested using the C2M 6-min duty cycle. These test cycles were designed to emulate the SAE J1088 Certification duty cycle (Gabele, 2000). The J1088 duty cycle is operated at two steady-state modes and separate emissions samples are taken during each mode. The first mode is defined as 100% of rated torque and 85% rated speed; the second mode is at idle or no load. In the C2M duty cycle, the engine is run through the same modes as found in the J1088 procedure, but only one emissions sample is taken continuously throughout the test. The time spent in each mode of the C2M is proportional to the weighting in the J1088 certification procedure: 90% is spent at full load and 10% at idle.

2.2. Fuel and oil types

All engines were tested using two fuels and two oils for a total of four fuel/oil combinations. The

two fuels (Haltermann Products Inc., Channelview, TX) consisted of a regular, unleaded summer gasoline (UNL) and a reformulated gasoline containing 10% ethanol (RFG). Target fuel specifications were chosen to be representative of the national average for these two types of fuel. These target specifications were not meant to agree with specifications for Indolene test fuel, which is used for most certification testing, but rather to mimic popular gasoline formulations used in the United States. Fuel drums were stored in an outdoor, temperature-regulated storage building at 15.5 °C. The two oils, a synthetic (SYN) two-cycle oil (Genuine Factory Parts #147543) and a “low smoke” mineral (PMX), two-cycle oil (Pro-Mix #54001), were purchased at a local retailer. Routine laboratory analyses were conducted on each fuel and oil; the results of these analyses are provided in the supplemental information section, along with specifications for Indolene certification fuel for

Table 2
Fuel/oil mixture designations and blend ratios

Fuel code	Fuel and oil mixture	Blend ratio (vol:vol) ^a	Oil (ml) per fuel (gal)
UNLPMX	Conventional gasoline and mineral oil	50:1	77
UNLSYN	Conventional gasoline and synthetic oil	40:1	95
RFGPMX	Reformulated gasoline and mineral oil	50:1	77
RFGSYN	Reformulated gasoline and synthetic oil	40:1	95

^aBlend ratios carried out per oil manufacturer's specifications.

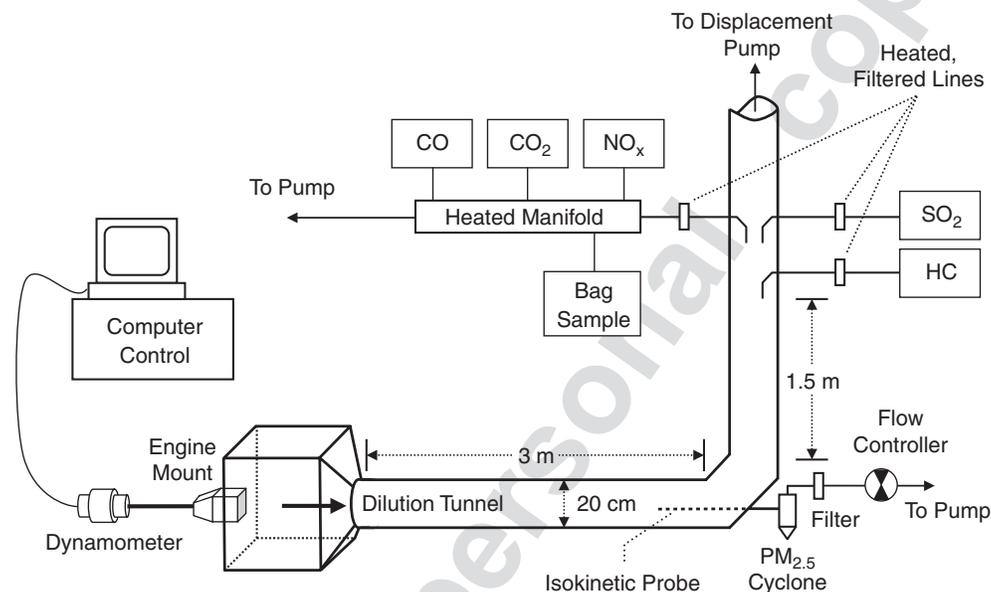


Fig. 1. Experimental schematic for dynamometer, dilution tunnel, and exhaust characterization.

comparison purposes. Oil was blended with the fuels in proportions recommended by the oil manufacturer, and each fuel/oil combination was given a unique code. Table 2 lists the fuel code designations and fuel/oil ratios for each of the four blends.

2.3. Exhaust dilution

Engine exhaust generated during testing was diluted using a constant volume sampling (CVS) technique (Gabele and Pyle, 2000). Engine exhaust was directed into the CVS dilution tunnel via a bell-mouthed, stainless steel flange positioned near the engine's exhaust outlet as shown in Fig. 1. Dilution air from the engine room formed an envelope around the exhaust and was drawn into the CVS tunnel with a positive displacement pump (Sutorbilt 5LVP, Gardener-Denver, Peachtree City, GA). The volumetric flow rate of dilution air plus engine exhaust was maintained at a constant rate of

$13.0 \text{ m}^3 \text{ min}^{-1}$ by the displacement pump. Temperature and pressure were monitored both inside and outside of the dilution tunnel to correct the actual volumetric flow to normal conditions of 760 mm Hg and 20°C .

The dilution tunnel is constructed of three main sections of stainless steel pipe with a diameter of 20.3 cm. Sections are connected with flanges and sealed with rubber gaskets. The first section of tunnel (a 3-m straight section) serves as the inlet and mixing area for the exhaust gases and dilution air. The second section consists of a 90° elbow that contains a port on its outside circumference that allows insertion of straight, isokinetic sampling probes for PM. Exiting the elbow, diluted exhaust enters the third, 1.5-m section, where sampling ports and probes for gaseous emissions are located. All probes, filters, manifolds, and sample lines for gaseous emissions were heated to approximately 112°C . Beyond the third section, stainless steel and PVC pipes (20.3 cm diameter) directed the exhaust

up five stories to the pump room on the roof, where the small engine exhaust exited to the atmosphere.

2.4. Emissions measurement

Analysis of regulated emissions included CO, HC, and NO_x. Emissions of NO_x were based on the molecular weight of NO₂ (the dominant species) and an average HC molecular weight of 13.87 g mol⁻¹ for each carbon atom counted. Additional, non-regulated emissions were also analyzed, including CO₂, SO₂, and PM_{2.5}. Gas analyses were performed using a Horiba Bag/Dilute-Modal Analysis Bench (Horiba Instruments, Ann Arbor, MI) that contains a Horiba Model FIA-34A-2 heated flame ionization detector for HC analysis, a Horiba Model CLA-53Ma heated chemiluminescence instrument for NO_x analysis, and Horiba AIA-23 non-dispersive infrared instruments for CO and CO₂ analysis. SO₂ analysis was performed with a pulsed, fluorescent ambient SO₂ analyzer (Model 43A, ThermoElectron Inc., Waltham, MA). All instruments exhibited a linear output over their calibrated ranges. Integrated (i.e., bag) analyses were used for emission rate determinations, while modal samples (real-time) were used to verify the bag analyses and to provide a detailed look at emissions over the course of the test cycle. Fine PM emissions were determined gravimetrically by drawing exhaust at 16.7 L min⁻¹ through an isokinetic probe followed by a 2.5 μm cut-point cyclone (University Glassware Research, Chapel Hill, NC). Fine PM was collected on pre-weighed, Teflon filters (Teflo 47 mm, Pall Life Sciences, Ann Arbor, MI) and allowed to equilibrate for a minimum of 24 h before final weighing. Filter weighings were conducted in a temperature and humidity controlled room using an analytical microbalance accurate to ±1 μg. Post-weighed filters were then stored in sealed containers at 4 °C for subsequent analyses.

Interior surfaces of the dilution tunnel were steam-cleaned prior to beginning the study to remove material that may have accumulated from previous use. During the course of the study, daily blanks were collected to determine background gas and PM levels. The blanks served as a check both for elevated levels of ambient pollutants and for potential contamination from the interior surfaces of the dilution tunnel.

Prior to each test, each engine was started, idled for several seconds, and then ramped up to the rated test speed and load. When both the engine surface

temperature and the continuous HC emissions stabilized, the C2M test cycle was started and sample collection began. At the conclusion of each test, the engine was shut off and allowed to cool while the regulated emissions were analyzed and other samplers were prepared for the next test. During this time, additional test fuel was added to the engine's fuel tank, if needed. Four sets of emissions tests were conducted on each engine, one set for each of the four fuel combinations. Each set consisted of multiple tests (six for the string trimmers and four for the chain saws), producing a total of 496 individual emissions tests. Statistical analyses were conducted with SAS software (ver 9.1, SAS Institute Inc., Cary, NC) using analysis of variance (proc GLM) and paired, two-tailed *t*-tests at the $\alpha = 0.05$ significance level. Prior to the analysis, data were transformed using Box-Cox maximum-likelihood power transformations to stabilize the distribution of variance across each pollutant data set. Only engines with complete data sets for all fuel/oil blends were included in the statistical analysis.

3. Results and discussion

3.1. Emissions

Emissions of regulated and non-regulated pollutants are shown in Fig. 2 for all pre-control, phase-1, and phase-2 engines. This figure shows an average of all fuel/oil combinations tested. Detailed emission results (CO, HC, NO_x, SO₂, CO₂, PM_{2.5}, fuel consumption) for each engine and fuel mixture are tabulated in the supplementary information section. Since engine size and power varied considerably from engine to engine, emission data were normalized to energy output by the engine (kWh) to provide a means of comparison between engines. Other units of emission factor (e.g., g L⁻¹ fuel or g min⁻¹) may be determined from the supplementary data as needed. Gaseous background concentrations remained relatively constant throughout the study and were generally only a small fraction of the diluted exhaust concentrations (HC < 4 ppm, CO < 1 ppm, NO_x < 0.01 ppm). Sample blanks for PM_{2.5} mass were negligible as compared to the sampled exhaust, representing less than 0.5% of the measured mass per filter, on average.

As expected, regulated emissions tend to decline with decreasing engine age or with the level of emission control, as seen in Fig. 2. This trend is

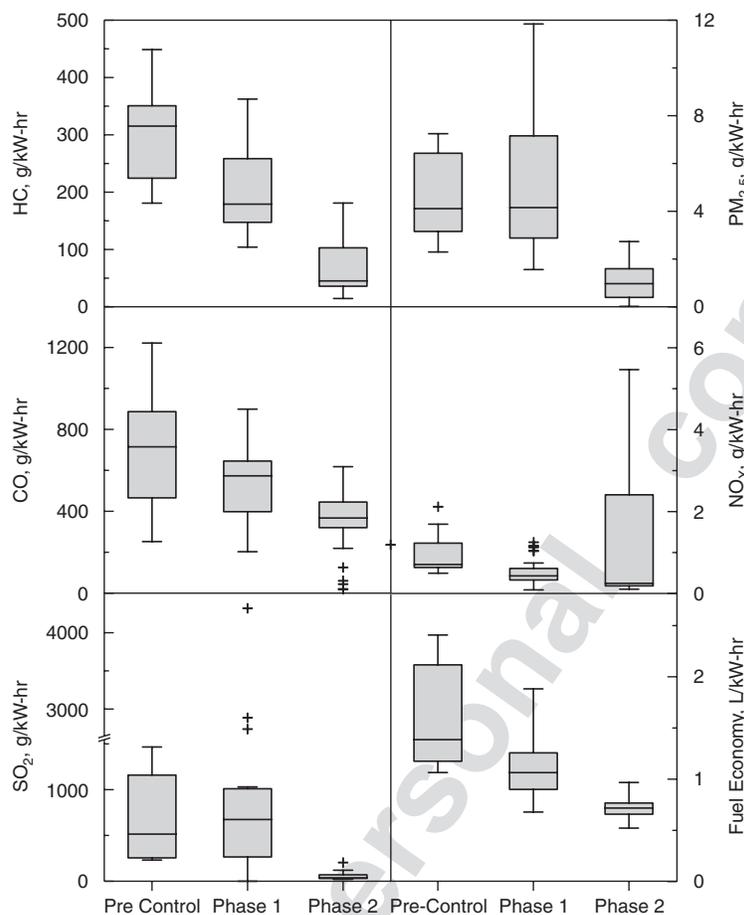


Fig. 2. Box-Whisker plots of handheld, 2-stroke engine emissions by pollutant and engine control type. Box limits represent first, median, and third quartiles of emission data. Error bars delimit the range of measured emissions. Outliers are represented by the (+) symbol.

clearly evident between pre-control and phase-2 models where large reductions of HC (78%) and CO (52%) occurred ($p < 0.0001$ in unpaired t -tests) indicating that phase-2 emission standards have had a positive effect on reducing overall emissions from handheld, small engines. Emissions of NO_x , on the other hand, show no statistically significant reductions between pre-control and phase-2 engines ($p = 0.15$). The apparent increase in NO_x between phase-1 and phase-2 engines (Fig. 2), however, is primarily related to two, high- NO_x emitters from the phase-2 category (including one 4-stroke hybrid engine, which typically emit NO_x at significantly higher levels than 2-stroke engines) that biased the emissions distribution upward; the median emission value for NO_x from phase-2 engines falls below that for pre-control and phase-1 engines. Nitrogen oxides are regulated in conjunction with HC emissions (i.e., $\Sigma[\text{HC} + \text{NO}_x]$) and although all of the phase-2 engines tested were within regulatory

limits, increases in NO_x emissions may occur as a result of the final, phase-2 rulemaking (EPA, 2000a). However, these increases will probably not enhance new ozone formation, even in NO_x -limited regions, as aggregate NO_x emissions from small engine lawn and garden equipment account for less than 0.5% of the national NO_x emissions budget (EPA, 2005).

No reductions in SO_2 and $\text{PM}_{2.5}$ emissions are evident between pre-control and phase-1 engines, however, phase-2 models exhibit significant reductions in both of these pollutants, comparatively ($p < 0.0001$). In general, PM emissions from small engines, though not regulated, are relatively high on a per engine basis. The median $\text{PM}_{2.5}$ emission factor for pre-control/phase-1 engines is approximately 4.1 g kW h^{-1} or about 37 mg min^{-1} when operating under the C2M-10 duty cycle at rated power, while the median $\text{PM}_{2.5}$ emission factor for phase-2 engines is 0.97 g kW h^{-1} or about

13 mg min⁻¹. For comparison, light duty automobiles with similar model years (1986–1997) emit about 3 mg min⁻¹ while operating at normal highway speeds of 60 mph (Knapp et al., 2003).

Most hydrocarbon emissions from 2-stroke engines result from unburned or partially burned fuel that short circuits the cylinder during the exhaust/intake stroke and exits the engine before the next compression/power stroke begins (Nutti, 1998). This phenomenon, known as scavenging loss, leads to a proportional increase in fuel consumption. Fig. 3 indicates a strong linear relationship ($R^2 = 0.89$) between HC emissions and fuel consumption (L fuel/kWh) for non-catalytic engines. Engines

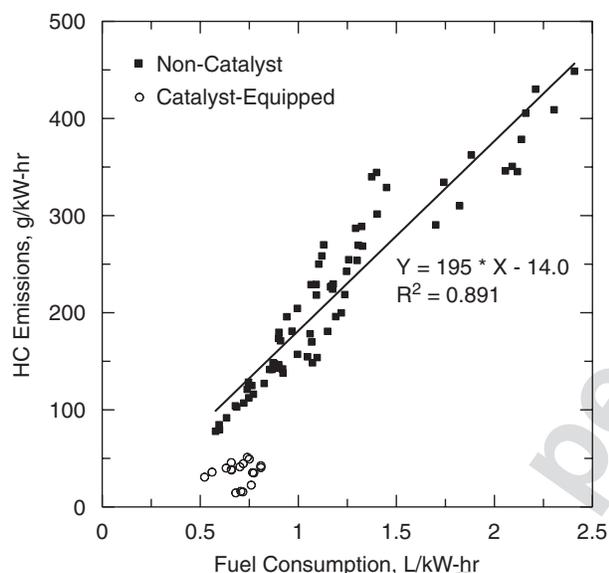


Fig. 3. Hydrocarbon emissions (HC) vs. fuel consumption for catalyst and non-catalyst engines for all fuel/oil combinations.

with catalytic controls are plotted separately for comparison, as catalytic converters are designed to inhibit HC emissions. A similar relationship, though less strong, is also evident from the regression of CO emissions with fuel consumption ($R^2 = 0.67$). All of the engines with catalytic controls fell under the phase-2 category and demonstrated the lowest HC and CO emission rates and the highest fuel efficiencies.

The distribution of total and individual carbonaceous emissions [CO+HC+CO₂] is shown in Fig. 4, where engines are arrayed chronologically according to their emissions 'phase' designation in order of decreasing engine age. The contribution from oxygen and hydrogen mass is not included in this calculation. Although carbon from PM_{2.5} emissions accounted for less than 0.2% of the total emissions budget for carbon and, therefore, are not included in the figure. As in Fig. 2, a general reduction in HC and CO emissions can be seen in Fig. 4 over time, while emissions of CO₂ tend to remain somewhat constant. Two factors probably contribute to these phenomena: catalysis and engine design. Catalytic converters, equipped on the newest phase-2 engines, transform HC and CO emissions into CO₂, thereby increasing the relative contribution of CO₂ to the carbon budget. Advances in engine design, on the other hand, lead to reduced scavenging losses and improved fuel economy. This, in turn, results in reductions of all three pollutants (CO, HC, CO₂) as the engine becomes more energy efficient and less fuel is lost to scavenging. Examination of Figs. 3 and 4 clearly indicate that industry-wide improvements in engine design for the phase-2 standards,

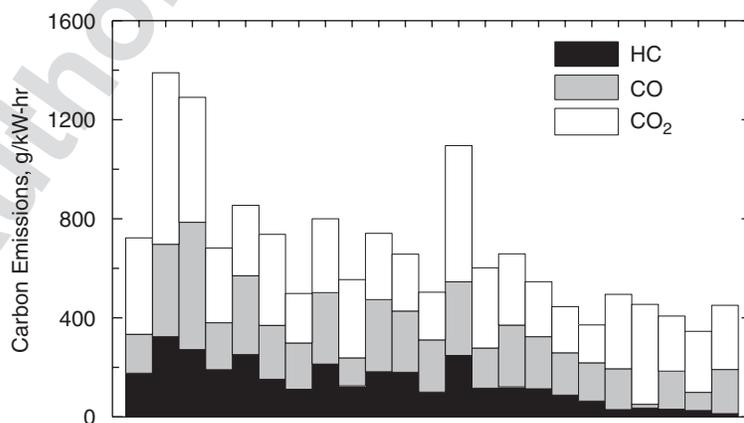


Fig. 4. Balance of carbon emissions from handheld, 2-stroke engines for all fuel/oil combinations. Average contribution from PM_{2.5} carbon was <0.2% of $\Sigma(\text{HC} + \text{CO} + \text{CO}_2)$ carbon. Units are grams of carbon per kilowatt-hour.

along with implementation of catalytic exhaust control, have resulted in significant reductions in overall emissions from small engines.

3.2. Fuel and oil effects

The use of reformulated, ethanol-based gasoline as an alternative fuel has increased dramatically in recent years (along with a proportional decrease in MTBE usage) (DOE/EIA, 2004). Consequently, a need exists to assess the effects of reformulated fuel composition on emissions. Therefore, analysis of variance and two-tailed *t*-tests were conducted to determine which fuel/oil mixtures resulted in higher or lower pollutant emissions for a given engine. The results of these analyses are shown in Table 3, which provides the ratio of emission factors (± 1 standard deviation) between two fuel/oil mixtures for each pollutant type. For example, a value of 1.14 ± 0.17 for the first entry, indicates that the UNL fuel tended to emit 14% more HC, on average, than the RFG fuel, with a standard deviation in the estimate of 17%. Emission ratios that are significantly different from unity are shown in bold.

As expected, between-engine variability is the strongest predictor of emissions for all pollutants in the ANOVA model ($p < 0.0001$). After accounting for the between-engine variability, however, several trends are evident. First, as mentioned above, HC emissions from engines using regular, summer-grade gasoline (UNL) are an average of 14% greater than for an engine running on RFG containing 10% ethanol regardless of the type of oil used. Likewise, fleet emissions of CO are 29% higher with UNL gasoline compared to the oxygenated RFG gaso-

line. Reduced HC and CO emissions with oxygenated fuels follow from a leaner air:fuel mixture, which is derived from the extra oxygen atoms present in the reformulated RFG fuel. Such reductions have been previously documented for a host of other engine types running on reformulated fuels (Bata and Roan, 1989; Pouloupoulos and Philippopoulos, 2003; Rice et al., 1991; Stump et al., 1996; Yacoub et al., 1998), though results are not always consistent (Magnusson et al., 2002; Pouloupoulos et al., 2001). Results from this study indicate that the use of ethanol-based fuel has a positive effect on reducing regulated emissions from small engines. Aldehyde emissions (e.g., formaldehyde, acetaldehyde), on the other hand, have been shown to increase dramatically with the use of ethanol-containing fuels (Magnusson et al., 2002; Pouloupoulos and Philippopoulos, 2003).

Emissions of CO₂ have been shown to increase with ethanol-containing fuels because of improved combustion associated with the leaning effect of ethanol (Hsieh et al., 2002), while emissions of NO_x tend to vary more with engine operating condition than on fuel composition (Hsieh et al., 2002; Magnusson et al., 2002). However, both CO₂ and NO_x show no statistically significant emission trends with any of the fuel/oil combinations tested here.

Emissions of SO₂ and PM_{2.5} are greater for the synthetic oil (SYN) as compared to the mineral-based oil (PMX), as seen in Table 3. The SO₂ trend contradicts the results from an analysis of sulfur content in the oil (ASTM D3120) provided in Table 2 of the Supplementary Information, showing similar sulfur contents in both oils. Other sulfur compounds, however, such as non-petroleum detergent additives within the synthetic oil, may have contributed to the increased SO₂ emissions and yet were not detected in the residual sulfur analysis. Increased emissions of PM_{2.5} are likely due to the manufacturer-specified blend ratio, shown in Table 2, which is 20% higher for SYN oil vs. PMX oil. To test this assumption, a short follow-up experiment examined the PM_{2.5} emissions that resulted from increased oil:fuel ratios. Four different oil:fuel blends were prepared using PMX oil blended with UNL fuel, representing oil:fuel ratios of 1:20, 1:32, 1:50, and 1:75, or volumetric oil contributions of 5.0, 3.1, 2.0, and 1.3%, respectively. Only one chain saw engine was run under the C2M-6 duty cycle, and the results of this short experiment are shown in Fig. 5. Emissions of PM_{2.5} are strongly correlated to

Table 3
Fuel and oil effects on exhaust emissions and fuel economy

	Fuel effect ratio			Oil effect ratio		
	UNL: RFG	<i>p</i> -value		SYN: PMX	<i>p</i> -value	
HC	1.14	± 0.17	(<0.001)	0.99	± 0.10	(0.375)
CO	1.29	± 0.53	(0.001)	1.00	± 0.20	(0.669)
CO ₂	0.99	± 0.09	(0.155)	1.20	± 0.58	(0.607)
SO ₂	1.35	± 0.95	(0.433)	1.73	± 0.89	(0.006)
PM _{2.5}	1.15	± 0.36	(0.100)	1.21	± 0.41	(0.010)
NO _x	1.09	± 0.51	(0.911)	1.10	± 0.38	(0.374)
Fuel use	1.03	± 0.09	(0.007)	0.99	± 0.05	(0.317)

Values represent the ratio of emissions (averaged by engine) between each fuel type (UNL vs. RFG) or each oil type (SYN vs. PMX) ± 1 standard deviation. Values in bold are statistically significant (paired *t*-test).

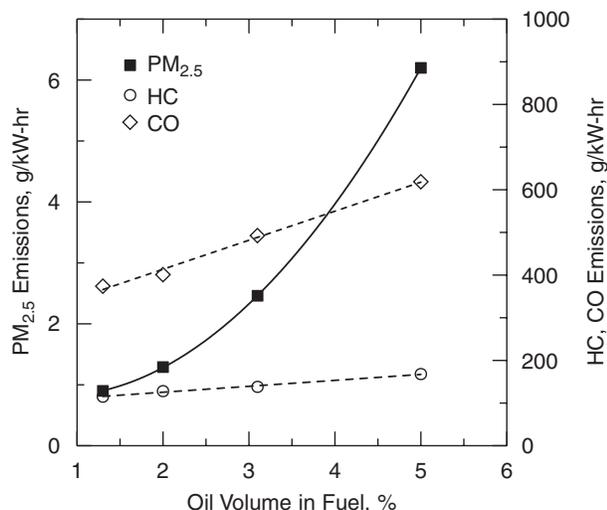


Fig. 5. Effect of oil:fuel blend ratio on emissions of PM_{2.5}, HC, and CO.

the oil content, as seen in Fig. 5. With a blended oil volume of 1.3%, PM_{2.5} emission rates were 0.90 g kW h⁻¹, while at a blended oil volume of 5.0%, PM_{2.5} emission rates increased to 6.20 g kW h⁻¹. We attribute these increased PM emissions to unburned oil that exits the engine in a similar manner to the scavenging losses discussed above. Interestingly, emissions of HC and CO also increase with increasing oil content in the fuel. Linear regression analysis shows a strong linear correlation between oil content and both HC and CO emissions, with *r*-squared values of 0.991 and 0.995, respectively.

3.3. Emission factors and air quality improvements

All of the newer, phase-2 engines tested here appear to be emitting at levels below EPA's phase-2 standards when new. However, engine emission factors tend to increase with engine age (Welch and Durbin, 2004). EPA has addressed this issue by incorporating engine deterioration factors into their certification requirements and emissions inventory models (EPA, 2002). Catalytic converter efficiency also may decrease over time (Burch, 2004) and current EPA estimates for catalytic engine deterioration factors are larger than for non-catalytic engines. Since emission estimates and potential improvements to air quality depend, in part, on the degree of engine deterioration over time, future work should address the effects of engine wear on emissions throughout the life span of newer, phase-2 engines.

Table 4

Comparison of emission factors (g kW h⁻¹) between current EPA, 2000a estimates and results from this study for class IV small engines

		EPA estimate	This study
Aged pre-control	HC	420	295 ± 93
	CO	1157	622 ± 226
	NO _x	1.26	0.96 ± 0.38
Aged phase-1	HC	311	196 ± 54
	CO	677	513 ± 174
	NO _x	0.69	0.44 ± 0.27
New phase-2 ^a	HC	36	42 ± 5.1
	CO	190	260 ± 170
	NO _x	2.0	1.5 ± 2.1

^aPhase-2—Catalyst equipped models only.

Although the operating histories (e.g., work-hours, work load, maintenance) of the engines tested here cannot be determined, we can compare emission factors from this study to current EPA estimates. Table 4 provides a comparison of emission factors of class IV engines between EPA estimates for the phase-2 rulemaking and results from this study for used pre-control and phase-1 engines and also for new catalytic engines (phase-2). For used pre-control and phase-1 engines, EPA estimates are slightly higher than the emission factors measured in this study. However, it should be noted that the values for used engines in Table 4 (pre-control, phase-1) represent worst-case estimates by EPA (2000a). For new phase-2 catalytic engines the agreement is better, indicating that EPA predictions for improved air quality due to the final phase-2 rulemaking appear reasonable.

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Appendix A. Supplementary materials

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.atmosenv.2006.08.033.

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